Changing climate space: A human perspective

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Climate change is having great effects on species and ecosystems around the world, and these effects will only increase in the future as the climate globally warms and alters in its functioning. Humankind is unlikely to be exempt from the risks of rapid climate change, and foreseeing and analysing these risks is important to future planning. We use ecological niche modelling techniques to investigate the links between humans, climate and risk in the future. We find that humans are extremely adaptable and inhabit nearly all varieties of climate regardless of its nature, although they are not distributed evenly. Cold and dry extreme environments, as well as extremely dry and hot environments, demonstrate markedly lower population densities than temperate climates. Tropically hot and wet climates possess some of the lowest and highest population densities even at the most extreme climate that is the limit of the climatic range available. Using this constructed description of humans and climate we project forward to the future and find that it is these most extreme climates that are most at risk of rapid climate change, and of developing novel or extinct climates in the future. Using created metrics of climate change risk, sociological elements are also introduced to investigate the direct risk to human populations. Those areas that face the triple threat of high levels of climate change, high population density and projected growth, and low regional GDP and resources are highlighted as hotspots of human risk from climate change. These are particularly prominent in central and South-East Asia, including many islands in Oceania, central Africa, the Amazon and the Andes.

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Chapter 1: General Introduction

Climate change is a great threat approaching humankind in the 21st century. Research presented by international organisations, such as the Intergovernmental Panel on Climate Change (IPCC, 2007a; 2007b) and other scientific bodies, warn of the possible dangers to human civilisation of a drastic change in global climate, such as increased threats of flooding, drought, heat-stress, spread of disease, changes in weather patterns and dramatic weather events and sea-level rise. There is also strong evidence to indicate that the climate is already changing rapidly, and that this is probably due to anthropogenic carbon emissions (IPCC, 2007a; Stern, 2006). The staggering amount of primary data required to understand our climate as it is, was and will be in the future is created, collated and presented by large-scale international cooperation between scientists working in multiple fields. Primary research includes everything from the physical properties of greenhouse gases and sunlight, the geophysical and ecological impacts of increased global temperature, to analyses of climate change on human societies and economics. From this data, many predictions have been made as to what the climate will do in the future, following trends in anthropogenic input and its effects on climate. Such predictions are often uncertain, but the possibility of even moderate change coming to pass would present huge threats to wide areas of the population.

Natural processes of climate change

The Earth's climate is an extremely complex system. Its currents, landmasses, topography, ice-caps, river systems, oceans and wind systems all contribute to what we call 'climate' in complex feed-back mechanisms that also come under the influence of external factors such as solar activity. This system has been in perpetual flux since the Earth developed its atmosphere and seas over 4000 million years ago (Kasting, 1993; Wilde *et al.*, 2001). The composition of gases in the atmosphere, the average global temperature and extent of ice-sheets have all varied over geological time. Historically, periods of substantial global warming and cooling over both hemispheres are linked to extensive volcanic activity and natural greenhouse gas emissions (Briffa *et al.*, 1998; Lamb, 1971) and variations in orbit (such as Milankovich cycles) and solar output (Berger & Loutre, 1991; Eddy, 1976; Hays *et al.*, 1976), with variations in both causing warmer and cooler periods in Earth's history. That changes occur over both hemispheres is an important indicator that changes in temperature are truly global, rather than regional, and such changes are surprisingly rare in Earth's history (Björck, 2011). Climate change is, and has been, a natural process. It has always been a major determinant of species evolution, adaptation and distribution throughout the paleoecological record, including human evolution (Demenocal, 2003; Kuper & Kröpelin, 2006; Vrba *et al*, 1995). It may seem improbable that humans could affect such a vast system, but the Earth's biome has always been an important contribution to climate; an oxygen-rich climate would not exist at all without photosynthesising organisms, and there are multiple warning signs that the Earth's climate is currently changing at an unprecedented and alarming rate. These indicators supply primary data to judge anthropogenic effects on the climate and form a basis for all future projections of our planet's future.

Anthropogenic Climate Change

It is estimated that the CO_2 concentration in the atmosphere is higher than for at least 80,000 years (Lüthi *et al*., 2008) and some estimate even longer (Tripati *et al.*, 2009). Emissions of carbon dioxide, specifically from fossil fuel combustion, increased by 40% between 1990-2008 and are so far tracking the highest and most pessimistic predictions of the IPCC (Nakicenovic *et al*., 2000; Le Quéré *et al*., 2009). CO_2 represents the single biggest contributor to the greenhouse effect and is often used as a popular overall metric for humanity's effect on the climate. Mean global temperature has been increasing by an average of 0.2 °C per decade since 1970 with a total increase of 0.74°C increase from 1906 to 2005 (IPCC, 2007a). Regional variation shows even more drastic changes when stable climates are ignored in the average. Arctic temperatures have increased at double the rate of mean global temperature increase (measured from the 19th century or 1960) (IPCC, 2007a).

These form the major drivers of the visible effects of climate change that have so far been measurable, but there are many corollaries and other minor effects, and for full details the IPCC Fourth Assessment Report is recommended. The most likely projections into the future predict greater greenhouse gas emissions, higher global temperatures, increased melting of the ice caps, higher sea levels and more extreme and disruptive climate events. While analogues from geological time are never perfect, previous interglacial periods are associated with warmer Arctic winters (Otto-Bliesner *et al*., 2008), smaller ice-sheets (Overpeck *et al*., 2006) and higher sea-levels (Kopp *et al*., 2009), all predicted to occur in the future at current rates of warming. These combined pose a significant risk to mankind. It is estimated that each doubling of CO_2 concentration in the atmosphere will produce a 1.9-4.5°C rise in temperature at equilibrium (Andronova & Schlesinger, 2001; Sherwood & Huber, 2010), though this is somewhat unpredictable (Roe & Baker, 2008). It is also estimated that the combustion of all remaining fossil fuels will produce 2.75 doublings of CO_2 (Montenegro *et al*., 2007). When combined with the potential amplification of carbon and methane release from permafrost sinks, the possibility of exceeding the 'safe' 2°C rise limit, often used by policy-makers and endorsed by the IPCC, becomes very real. A rise of this nature would have drastic effects around the globe. The risks presented are diverse and vary depending on the resources and resilience of the human population to these changes, but they are all likely to have global impact.

Sea-level

Increases in air temperature correlate with a decrease in ice mass, especially above 65°N. As could be expected with an increase in ice melt, sea levels have also begun to rise. Global sea levels have risen by an average of 3.4 mm annually since 1993 (Cazenave *et al*., 2008). This observed sea level rise is 80% faster than the best estimates presented by the IPCC in 2004 (IPCC, 2007a), and as a result sea levels are likely to rise much higher than the projected 18-59cm estimated for the next century by the IPCC. As the oceans get progressively warmer, sea levels will rise more rapidly (Rahmstorf, 2007), approximately 40% by thermal expansion and 60% by increased meltwater from glaciers and the icecaps (Domingues *et al*., 2008), leading to a sea level rise by anything up to 2m by 2100 (though more likely by around 1m) (Rahmstorf, 2007; WBGU, 2006). Over 160 million people live within one metre above sea-level and these populations could be at risk within the next century (Allison *et al*., 2009).

Weather

The less direct effects on weather patterns and precipitation pose no less of a threat to livelihoods and agriculture. Disruptions in normal weather systems would have huge potential to negatively affect large sections of the population, as gradients between cold and warm fronts would increase the severity and frequency of cyclones, hurricanes and other extreme weather events (Hoyos *et al*., 2006; Mann *et al*., 2009). This can be primarily attributed to projected increases in average wind-speeds from greater temperature gradients (from warming of the Earth's atmosphere) and higher ocean surface temperatures (Elsner *et al.*, 2008; Emanuel *et al*., 2008). Impacts in weather systems would also include changes in precipitation events, leading to potential increases in drought-vulnerable areas (Wetherald & Manabe, 2002) and in flood-prone areas (Kleinen & Petchel-Held, 2007; Monirul Qader Mirza *et al.*, 2003). It is estimated that while river runoff and water availability will increase in already wet or tropical environments, some dry regions will become more so, adding to water stress particularly in developing countries (Manabe *et al.*, 2004). Extreme heat and cold events will also probably become more common (Karl *et al.*, 2008). Again, there is some evidence that this is already happening to some extent. Sheffield and Wood (2008) note that there has been a marked increase in drought events since the 1970s, correlated to a decrease in precipitation in these areas. Burke *et al*. (2006) estimate that the proportion of land-area susceptible to extreme drought will increase by 30% by the end of the 21st Century, causing a real risk of famine and population decline in already arid areas.

Agriculture

A trend to shifting weather patterns puts agriculture at risk on a regional scale. As droughts and floods become more common and rainfall becomes less predictable, it is expected that agricultural communities, especially subsistence level ones, will be both severely positively and negatively affected (IPCC, 2007a; Olesen & Bindi, 2002; Reilly *et al.*, 2003; Tubiello & Fisher, 2006). Many urban populations are supported by vast areas dedicated to crop growing. In particular, the mid-west United States, the east of Europe and the paddy fields of southern China support huge numbers of people across the world. If these productive areas were to be adversely affected by climate change the resulting decrease in agricultural productivity would have a huge impact on countries and economies across the world (Monirul Qader Mirza, 2002; Nearing *et al*., 2004; Rosenzweig *et al*., 2002; van Ittersum *et al*., 2003). The exact nature of how rain patterns will shift is still not precisely understood (IPCC, 2007a), but must still be recognised as a potential threat. Similar arguments can be applied to ecosystem collapse in some areas, which would certainly adversely affect many local populations (IPCC, 2007a), though once again specific predictions are extremely challenging due to the complex nature of the systems in question (Malcolm *et al*., 2006).

Heat Stress

Temperature rises will also create significant areas that will become vulnerable to heat stress unless there are significant increases in energy infrastructure (McMichael *et al*., 2006; Sherwood & Huber, 2010). Once the ambient temperature (wet-bulb equivalent) reaches above 35°C for prolonged periods of time then humans are no longer able to passively lose heat, causing a huge increase in heat stress related illnesses and mortality (Sherwood & Huber, 2010). Currently this does not happen in any inhabited areas, but is a real danger in worst-case temperature rise scenarios. This is possible in many desert areas, especially North Africa, Australia and South America (Sherwood & Huber, 2010), even to highly acclimatised individuals (Bynum *et al*., 1978; Mehnert *et al*., 2000). This is something of an under-investigated possible risk, but in scenarios where the global temperature increases by more than 7°C then it is a very real threat to very large areas of the population.

Health

These changes added together are expected to have large effects on the health of many populations around the globe. Key concerns are increased malnutrition from increased drought and agricultural collapse, especially in poorer, subsistence-level areas; increased danger from fires, floods, storms, hurricanes and other extreme weather events and the unknown alterations to many infectious diseases, especially those carried by animal vectors (IPCC, 2007a; Patz *et al.,* 2005*)*. True predictions of how many this will affect are always very uncertain, as background socio-economic factors are also involved, so many take the approach, as we will now, of identifying these as risks to multiple societies.

Migration and security

With increasing climate change risk, lower food security and higher health risks, many countries will face great challenges, especially those already suffering from population pressures, poor healthcare and low income. In areas of existing political instability or weak governmental infrastructure there is a risk of increasing instability and conflict, thus exacerbating the situation

(Barnett & Adgar, 2007; Nordås & Gleditsch, 2007; Reuveny, 2007; UNEP, 2011). With increasing instability and other risks, migration of displaced people is likely to increase from vulnerable areas (Black, 2008).

Risk Assessment

With the data and understanding of the climate formed so far, forming accurate risk assessments is one of the primary objectives of climate change research. Response to these dangers is one of the major international political challenges of the 21st century. Consultancy frequently comes from the Intergovernmental Panel on Climate Change (IPCC), and for a more detailed discussion of many of the factors discussed here, their fourth report is recommended. However, while they identify many factors that could affect mankind, they do not carry out specific area risk-assessments on anything more regional than a continent scale. Other reports, however, do focus on much more regional or gridded assessments (e.g. Anyah & Semazzi, 2004; Arnell *et al*, 2005; Black, 2008; Ekstrom *et al*, 2007; Kumar *et al*., 2006). Multiple approaches have been tried in order to model and estimate risk to human populations from climate change (Jones, 2001; Patz & Balbus, 1996; Parry *et al.*, 1996; Parry *et al*., 1999; Pittock *et al.*, 2001, Torresan *et al.*, 2008). In this project we will use the well-established system of climate niche modelling, used frequently in conservation and ecology literature, to apply it to humans and the risk faced from climate change.

The Niche

What determines where species live? What factors contribute to life-history and population ecology? How do we measure these? These have been key questions that form the foundation of ecological studies. Decades of study have led to an understanding of not just species attributes but relationships to other species around them on every trophic level and their surrounding environment. Increasingly we understand abiotic ecological factors to be crucial to understanding the survival, dispersal, distribution and life-history of a species. The conditions that are capable of supporting a particular species can be modelled in space to represent the fundamental niche. This includes some or all of the following: temperature, rainfall, topography, wind patterns, distance from water sources or the ocean and so on. A subset of these comprise the climatic niche. A species may not, and usually does not, occupy the entire of its potential (fundamental) niche, what it instead inhabits is its realised niche. This theory of realised ecological niche and its subsidiary climate niche, first presented by Grinnel (1917; see also Grinnel, 1924), forms the basis of many ecological techniques to describe species lifestyle, behaviour and adaptation. It is also a useful basis for understanding shifts in species range over time. While there are limitations, correlative models can never be exact, it forms a powerful tool to analyse past, present and future effects of climate on species. By explicitly including climate factors and correlating distribution to these factors the drivers behind population growth and expansion can be investigated within a species niche (Hutchinson, 1957). It is worth noting that such models can never include all climatic factors and do not explicitly include biotic factors that affect species range (Davis *et al*., 1998; Schweiger *et al*., 2008). A realised niche cannot therefore always predict how a species will react in a new area that has identical climate variables to its previous range, but has different biotic factors, e.g. a lack of predators, or how a species will respond in areas outside of the parameters the niche was calculated within.

Niche modelling

Ecological niche modelling has been applied successfully in diverse ways to many different species. It can be used to understand distributions of single species with potential for conservation advice (e.g. Buse *et al*., 2007; Hu *et al*., 2003; Huntley, 1989; Swartzman, 1995), predict range shifts in species due to climate change (e.g. Barrows, 2011; Carroll, 2010; Estrada-peña & Venzal, 2007; Parmesan *et al*., 1999; Tingley *et al*., 2009) or even to predict shifts of whole ecotones and sets of populations (e.g. Gasner *et al*., 2010; Johnson *et al*., 2011; Lucey *et al*., 2010; Pounds *et al*., 1999; Sagarin *et al*., 1999). It forms a singularly powerful correlative or mechanistic tool to attempt to understand a species' link to its climate space.

Using this approach, as well as direct observational methods, responses to climate change by multiple species and taxa have been shown and projected. The continuing change in climate has caused range and migration pattern shifts, and many noted patterns of phenology changes (Menzel, 2000; Parmesan, 2006; Walther *et al*., 2002). Commonly quoted examples are those of Arctic species moving northward to follow colder temperature gradients and various plants and insects expanding their ranges northward as winter conditions ameliorate (Hill *et al*., 2002; Parmesan *et al,*. 1999; Sturm *et al*., 2005). In some cases these contractions in range have been large enough to contribute to extinction events (Hickling *et al*., 2005; Parmesan, 2006). In fact, responses to climate change have been recorded in almost every taxa (Badeck *et al.,* 2004; IPCC, 2007a; Parmesan, 2006; Parmesan & Yohe, 2003; Walther *et al*,. 2005). Of particular note are the adverse effects of warming and sea level rise on tropical reefs and amphibians across the world as the changes have been so wide-spread and catastrophic (Hoegh-Goldburg; 1999; 2002; Pounds *et al*., 2006). When projecting into the future, responses from species vary and include large range expansions or biological invasions, severe contractions in range leading to possible extinctions, changes in ecosystem assemblages leading to non-analogue communities or sometimes the response remains unpredictable (Parmesan, 2006; Walther *et al.*, 2005). As climate change continues throughout the next century, we can only expect these responses and unpredictability to increase and worsen. To attempt to predict these ecosystem responses, niche modelling has become an invaluable tool for conservation planning and projections of species in the future. While many other species are of conservation concern, it would be unwise to assume humanity will remain unscathed by these changes to both the climate and the ecosystems around them.

Previously few attempts have been made to measure humanity's realised or fundamental niche, and similarly using this approach to measure effects of climate change on human populations has not been fully exploited. At first glance, it may seem counter-intuitive to consider human population centres to be bound by geographical parameters. After all, humans have such advanced technological means that we can improvise to live anywhere, even in the vastness of space given enough resources, and our cities support extremely large, apparently unnatural densities of people. However, two arguments can be used to support a more ecological and geographical explanation to human distribution. One, current distributions of human population are often centred on past settlement, which were often determined by its geographical location and climate. Two, the nature of human population spread can still be considered in terms of niche. The ability that humans have, that is to use tools and knowledge to expand into previously uninhabitable areas, is simply a method of expanding the species' fundamental niche. We also manipulate the ecological constraints of an area through agriculture and domestic animals to produce a biome more beneficial to us. Humans can now live in many different climate zones, far more than our simple physiological limits would suggest.

This adaptation to extreme temperatures is achieved in the modern world by the consumption of energy. While many indigenous peoples have survived in some of the most extreme places on Earth, large populations are sustained by a huge consumption of energy. Approaching from a different angle, the energy available for us to use is a limiting factor of our fundamental niche. As climate change will sooner or later likely coincide with an energy crisis as oil and coal become scarce, excepting a huge increase in the utilisation of renewable energy sources, then it can be expected that the range of habitats we are capable of exploiting will decrease.

The human climatic niche

While humans are globally distributed, their regional distribution varies greatly. If there is a strong link between where humans live and the associated climate variables, then human distribution can at least be partially explained and predicted by climate variables. Samson *et al*. (2011) suggest that 40-60% of current human density can be explained by their climate model and that, of the many climate variables available from global weather-stations, four represent extremely important factors that affect human populations. These four are: annual mean temperature, mean temperature diurnal range, total annual precipitation and precipitation seasonality. These four form the primary factors for investigation. Samson *et al*. (2011) also note that the strength of the link between climate and population density is very regionally variable. Niche modelling is a very successful method of modelling responses to climate change and here we apply it to climate change effects on humans. There is some evidence that climate change, not only climate, has historically influenced human population developments (Kuper & Kröpelin, 2006; Weiss *et al*., 1993, Zhang *et al*., 2007). By combining bioclimate modelling and climate change predictions, a new form of risk analysis can be carried out. Measuring local climate change magnitude and the nature of change on ecosystem functioning provides information on risk that human populations will face in the future. This adds to existing climate change risk and mitigation literature whether it be global (Dyson, 2005; IPCC, 2007a; Stern, 2006), or regional assessments used to inform policy (Lobell *et al*., 2008; IPCC, 2007a; Patz *et al*., 2005; UN, 2009; WHO, 2004) . Climate change is likely to have drastic influences on human populations, and any measure of quantifying this change on a more local scale can help identify key risk areas.

Outline of Thesis

There are two overall aims to this thesis:

1) to analyse the relationship between climatic conditions and human population density at the global scale;

2) to use this relationship to quantify different aspects of risk to human society from future climate change.

To this end, the three main chapters of the thesis have the following objectives:

Chapter 2: To quantify and map the current spatial distribution of human populations in global climate space. Population density distribution within climate space is examined and the possible links between humans and climate are considered. Within climate space the significance and strength of various climate factors and effects on human distribution across the globe are also discussed.

Chapter 3: To analyse shifts in global climate space under projected future climate change by 2050 and to evaluate the consequences of these shifts for human populations. Using projected climate data and a constructed climate space, various measures of climate change are investigated.

Chapter 4: To develop and apply risk metrics to quantify combined effects of various aspects of climate change on human populations. Sociological elements are also introduced. Using combined climatic and sociological measures we also suggest what areas in general will be the most adversely affected by climate change.

Chapter 2: Current Globally Inhabited Climate Space

Abstract

Background: Human distribution and populations have been and are still linked to the Earth's climate. While humans are complex society-driven animals, the effects of climate variation are still an important factor in their distribution and spread.
Methods: Using an ordination model, multiple climate factors are included to create a global "climate space", a multi-dimensional map of the world's climate. Within this climate space human population density is mapped and linked to climate. We attempt to isolate the climate ranges that characterise low, medium and high human population densities.
Findings: We find that each population category inhabits unique, though overlapping, areas of climate space. Very low population densities are found particularly in cold, dry environments, as well as extremely hot and dry environments, characterised as marginal climate space. Medium densities are found throughout central and extreme climate space characterised as hot and wet. Very high population densities are found typically away from the centre towards the areas of climate space representing the Tropics, often right up until the very edge of available climate space.
Conclusion: Humans are not centrally distributed but favour tropical edges of climate space even including the most extreme climates available. There is much in their distribution that is not directly explained by climate, but the results show it is still a strong predictor/indicator of population density.

Introduction

Niches

All species inhabit what is termed their niche. Characterising species niches has been one of the foundations of ecology and has been used extensively since its conception (Grinnel, 1917; Hutchinson, 1957). The effects of environment and climate form one of the most important factors that determine species spread and life-history. The study of climate effects on species distribution and population dynamics has a long history, alongside studies of biotic interactions between species such as competition and population density effects (e.g. Farrow, 1917; Klopfer & MacArthur, 1961; review in Holt, 2009). There are very few species with the flexibility of traits to allow them to inhabit every and all environments (humans are something of a special case, using tools to expand their fundamental niche), and to do so would approach one of the traits of the fabled "Darwin's Monster". Instead species possess traits that allow them to gain a competitive advantage in the environment they live, whether that may be greater drought tolerance or adaptions to make better use of resources. Conversely, due to the usual presence of a physiological trade-off, species do less well outside of these conditions and fail to spread and reproduce as well. Examples abound of this, whether it be a low frost tolerance making northern expansion impossible or an inability to reproduce without rain at certain times of the year. Forming an accurate ecological niche involves measuring or calculating these boundaries and produces a characterisation of a species in climate. Niches are typically estimated as either a fundamental niche using physiological data (review in Kearney & Porter, 2009), or a realised niche by using presence/absence population data which cover all climatic factors in which a species is found (review in Pulliam, 2002). A realised niche is formed by an overlay of climate and population data to find the full range of habitats that a species currently inhabits, and is often a more rapid method than calculating physiological limits.

When a realised niche is constructed within the total range of climatic conditions that currently support a species it can be visualised as a climate space. Extending from Hutchinson's niche "hypervolume" (1957), a climate space describes boundaries in species distribution using climatic variables affecting species functioning and lifecycle, such as mean daily temperature, annual precipitation levels and seasonality. The number and strength of explanatory power of each climate variable varies from species to species, producing unique climate spaces for each. The more relevant factors included the more accurate and consistent a modelled space becomes. Using a correlative method the species climate space (or niche) may only consist of the species' current range, or it may show other geographical areas that are theoretically suitable but have not been colonised for one reason or another. By extrapolating such a constructed space with future climate variables an estimate can also be made of future population trends and range shifts. The boundaries described in climate space at which species can no longer exist effectively represent the edge of their inhabitable climate space. These climate space limits can be caused by an upper physiological stress limit (e.g. Angert, 2006; Hoffman, 2010; Stillman, 2002), or a limit to suitable habitat associated with other biotic factors (Gaston, 2009). These boundaries, influenced by both physiology and climate, have been recognised for many decades generically as species biomes, such as 'forest' or 'desert' species.

The patterns and limits of species boundaries in climate space can be represented and analysed in multi-dimensional space, and allows modelling across multiple climate variables simultaneously to help understand the ecological and geographic patterns in species distributions. There are multiple applications of this method and the concept of climate space has been used to investigate many aspects of species demography. Climate space can describe the contributing climatic factors that act as predictors of population distribution (Chuine & Beaubien, 2001), and as a measure of the ecological niche of species (e.g. Fang & Lechowicz, 2006; Vetaas, 2002), sub-species (Diniz-Filho *et al.*, 2000; Martin & Omland, 2011) and populations (e.g. Harrison *et al*., 2006). It also forms the basis of a variety of methods to describe range shifts and colonisation patterns of species (Stralberg *et al*., 2009), and used to predict future needs for conservation areas (Araujo & Williams, 2000; Wiens *et al*., 2011). As such it has been used to investigate a multitude of subjects, from ancient species ecology (Nogues-Bravo, 2009; Ohlemüller *et al*., 2012; Roberts & Hamann, 2012), to exploring speciation mechanisms (Kozak & Wiens, 2006), invasion patterns (Broenniman *et al*., 2007; Higgins *et al*., 1999; Hill *et al*., 2012) and future range distributions of multiple species and assemblages of species in response to climate change (Kelly *et al*., 2012; Ohlemüller *et al*., 2008; Pearson & Dawson, 2003). As such, climate space methodology is flexible and informative. By being able to quantify parameters in which a species is found, climate space modelling forms a powerful tool to investigate past, present and future distributions and to understand population ecology in relation to climate.

Humans and climate

As with other organisms, human settlements are mediated by environmental factors at a local scale, particularly the local relief of the land, proximity to water and in relation to previous settlements (Kummu *et al*., 2011). Humans have a physiological limit like any other organism, albeit one expanded by technological means, it seems logical that more suitable habitats are more likely to be heavily populated, allowing application of a bioclimate niche modelling approach. Certainly, based upon archaeological data, this has been the case in the past and sudden changes to local climate have had adverse effects (Beck & Sieber, 2010; Cullen *et al*., 2000; Haug *et al*., 2003). Key climatic factors likely to affect human population spread are those associated with gross temperature averages and precipitation levels, and the frequency and severity of extreme climate events within an area, such as driest and hottest months (Zhang *et al*., 2007). These factors also tend to be collinear with agricultural availability of an area (Samson *et al.*, 2011), along with precipitation seasonality.

There are added complications of applying niche modelling to humans, as human population spread is often linked to historical factors and local resource patterns and the complex sociological nature of human demographics (problems which are also associated with other species (Pearson & Dawson, 2003)). Despite this, Samson *et al.* (2011) concluded that human population distribution can be at least partially explained by climate variables and of a comparable explanatory power to that of niche models for other species (e.g. Iverson *et al*., 2008; Rodenhouse *et al*., 2008), although the strength of the link between climate and population was greatly variable. Four components particularly, mean annual temperature, mean diurnal range in temperature, total annual precipitation and precipitation seasonality, contributed to explain approximately 50-55% of human population spread and density according to Samson *et al*.'s (2011) geographically weighted model. We expand on this idea to explore not just how strong the links are between climate and human population density, but the utilisation of this climate space by mankind and how humans occupy this multidimensional space.

Here, we investigate patterns of distribution of human population densities throughout global climate space. In other species, distribution in climate space is usually limited, something which we do not expect to find in this case as humans are a global species. We use several methods to characterise patterns of human distribution. As a form of null hypothesis it may be expected that human populations will favour central climate space, away from extreme climates, and become less numerous nearer the edges of climate space. It is assumed that particularly extreme climates away from the central conditions of distribution are less amenable to habitation, due to extreme heat, cold, drought or flooding. If this does not prove correct, the next stage of investigation concerns what climatic characteristics do humans favour. To quantify the question of preferred human climate space, the marginality and overlap between regions with different population densities will also be investigated.

The following three questions will be addressed:

1) How are human populations distributed across global climate space?
2) What are the climate characteristics of regions with low/medium/high population densities?
3) What is the marginality of and the overlap between regions with different population densities in global climate space?

Table 2.1: The 19 bioclimatic variables used to construct the multidimensional climate space, using data from WorldClim (Hijmans *et al*., 2005)

Climatic Variables
1. Annual Mean Temperature
2. Mean Diurnal Range (Mean of monthly (max temp - min temp))
3. Isothermality
4. Temperature Seasonality
5. Max Temperature of Warmest Month
6.Min Temperature of Coldest Month
7. Temperature Annual Range
8. Mean Temperature of Wettest Quarter
9. Mean Temperature of Driest Quarter
10. Mean Temperature of Warmest Quarter
11. Mean Temperature of Coldest Quarter
12. Annual Precipitation
13. Precipitation of Wettest Month
14. Precipitation of Driest Month
15. Precipitation Seasonality
16. Precipitation of Wettest Quarter
17. Precipitation of Driest Quarter
18. Precipitation of Warmest Quarter
19. Precipitation of Coldest Quarter

Methods

Climate and Population Data

Global climate space was characterised and quantified using 19 WorldClim bioclim climate variables (Hijmans *et al*., 2005; Table 2.1). Population density data were acquired from the adjusted GPW3 dataset (CIESIN, 2005). All variables were aligned by latitude and longitude in a single file with population density and all 19 bioclim variables at a resolution of 0.5° with a total of 53,300 grid cells. Due to the presence of both extremely low and extremely high population density grid cells, population density data was transformed and separated into categories on a logarithmic scale. These categories were described with population density boundaries of 0, 0-1, 1-10, 10-100, 100-1000 and >1000 people per square kilometre, labelled as 'NoPop', 'VLowPop', 'LowPop', 'Pop', 'HighPop' and 'VHighPop' respectively throughout the thesis. Figures were all produced in R (v2.12.2).

Ordination Analysis

To investigate the occupation of climate space in all climate variables simultaneously and to investigate marginality of human population density, Principal Components Analysis (PCA) ordination analysis was carried out. This simplifies multi-dimensional space into one or two axes to allow graphical and statistical comparison of climate or niche spaces. The generated PCA axes explain multiple climate factors at once and direction is equivalent to multiple covarient changes. When graphed climate space is visualised in two axes which explain 53% and 24% of total climate variation respectively (a third adds an additional 7%). PCA measures the power and response curve of population to each climate variable and constructs a climate space giving preference to those variables that have most explanatory power. Within this constructed space human climate space was plotted and linked to the population density of each gridcell. By comparing the spread and distribution of human population density within climate space the distribution and links between humans and climate were investigated.

Marginality analysis measures the position of different population density categories within climate space compared to the centre of climate space. This measure of position and marginality was conducted in R (v2.12.2) using the *ade4* package and was based on the 'niche' command which uses the outlying mean index as its basis (Doledec *et al.*, 2000), and verified with PCA. Treating each population category as a sub-population of total global population an OMI measures the relative niche of each category in climate space. This produces both the distance of each population category from the global average (the centre of climate space), referred to as each niche's OMI, its tolerance, the relative size of each niche, and its inertia, a measure of confidence and number of outliers outside of the population niche. A higher inertia indicates fewer outliers.

As an alternative method of comparing population categories within climate space, statistical ordination was done using the BIOMOD package and was based upon the methodology and source code laid out by Broennimann *et al.* (2012). This initially produces a method of measuring density distribution and a population category's position within climate space, but also compares population categories and their independence of each other and their relative position. Using the 'PCA-env' command, pairs of niches can be compared to measure relative overlap between them and this was carried out for every combination of population category to produce a D statistic measuring niche overlap of each pair (review in Warren *et al.*, 2008). D measures the proportion of overlap between population categories, on a scale between 0 and 1 (representing 0 and 100% overlap respectively), measured from within the climate space created by Principal Components Analysis (PCA). Population categories with a low overlap are positioned further apart in climate space. Since the ordination technique used for this is independent and weighted differently to the global space the D-space when graphed appears mirrored and on a different scale range. Since ordination axes are arbitrary this is not significant, as the relative measure, position and shape of climate space remain the same and results are still comparable.

Results

Climate space currently occupied by humans

People today inhabit most areas and most climate regimes on earth. Only 2.4% of our grid cells had a population density of 0 (Table 2.2). Provided in Figure 2.1 is a constructed global climate space with 19 climatic variables for all population categories. Zero population grid cells are concentrated at the very cold and dry parts of the global climate space with low precipitation seasonality and small daily temperature ranges (Fig. 2.1). No population areas also are located the farthest away from mean climate conditions (highest OMI values, Table 2.2) and show the smallest climatic niche breadth of all population categories (smallest tolerance values, Table 2.2). Very low population grid cells form the largest population category and are much more widely spread through climate space and possess the largest niche breadth (highest tolerance values, Table 2.2). Very low population cells are particularly prominent in very cold dry areas and very hot dry areas, and are the primary population category on the edge of climate space (medium high OMI value). Low to medium population densities are the most centralised categories and are associated with low to medium temperatures and precipitation and have a more limited distribution in climate space (small OMI values). High population densities have similar niche breadth but are distributed further from the global mean towards high extremes of both temperature and precipitation and lower annual variation of precipitation and temperature

Table 2.2: Summary results of Outlying Mean Index (OMI) analysis. Included are the size of each population category (percentage of total grid cells), the inertia (number of outlying points), OMI values (average distance of each category from global mean) and tolerance (size of category in climate space).

Population Category	Proportion	inertia	OMI	Tol
NoPop	2.4%	24.846	21.979	1.873
VLowPop	40.7%	20.215	2.035	10.585
LowPop	24.1%	18.021	0.506	6.813
Pop	22.8%	18.297	1.718	5.868
HighPop	9.5%	17.459	1.960	5.911
VHighPop	0.5%	19.691	2.349	6.911

(higher OMI, Fig. 2.1; 2.2). High population density grid cells also exist right up until the edge of climate space (Fig. 2.1). Very high population density grid cells are the smallest category and represent typically urban areas and as such are scattered throughout climate space with little clustering (Fig. 2.1)

Preferred Climate Space

OMI results allow characterisation of each population category in climate space and describes a category's average distance from the global climate mean and its tolerance which describes the size of the population category. Although there is a large overlap, high population densities are not increasingly centralised (OMI values, Table 2.2). Rather, medium-density populations are more centred and as population both decreases and increases the category moves further away from the global mean (larger and smaller OMI values, Table 2.2). Very low population densities are the most wide-spread niche, and no population grid cells the smallest, but otherwise tolerances are similar (Table 2.2).

More generally there does appear to be evidence that climate is linked to human population distribution, though in some areas more than others. Temperature factors and precipitation factors as groups tend to be highly collinear, but extremely low temperatures and precipitation gradients are typically linked to lower population densities (Fig. 2.1; 2.2). When looking at four key climate factors there is no simple pattern of highly centralised climate space (Fig. 2.2) and in either case high population densities often exist right up to the edge of the existing range of a climate variable (Fig. 2.1; 2.2).

From this analysis it seems that although humans are less common in marginal climate space in the cold and dry areas of the Earth, marginal climate space in areas of high temperatures and high rainfall, in other words the tropics, both high and low population density grid cells are present in equal quantity. However, in central climate space there is a much higher proportion of medium to high populations density grid cells, and less very low population density grid cells.

Overlap and Position of Niches

Table 2.3: Summary of D statistics indicating niche overlap between pairs of population categories. D represents proportion of overlap on a 0-1 scale.

D value of Overlap	NoPop	VLowPop	LowPop	Pop	HighPop	VHighPop
NoPop		0.161	0.055	0.057	0.064	0.075
VLowPop	0.161		0.489	0.365	0.385	0.385
LowPop	0.055	0.489		0.638	0.592	0.532
Pop	0.057	0.365	0.638		0.689	0.543
HighPop	0.064	0.385	0.592	0.689		0.693
VHighPop	0.075	0.385	0.532	0.543	0.693	

The OMI gives an indication of position of each niche and it is already apparent they possess some different qualities to each in position and niche breadth. However, there is a great deal of overlap between population categories so a measure of overlap is useful to confirm the individuality of each niche. The D statistic (Table 2.3) measures the degree of overlap between niches and indicates the level of isolation of each niche. The zero population category appears as the most isolated, with very little percentage overlap with any other niche (Table 2.3, Fig. 2.4). All other niches show the highest degree of overlap with their nearest population categories, but never over 70% overlap. This means each has its own individual pattern in climate space but there is a great deal of space where multiple population category grid cells co-exist, especially in the high temperature and precipitation extremes.

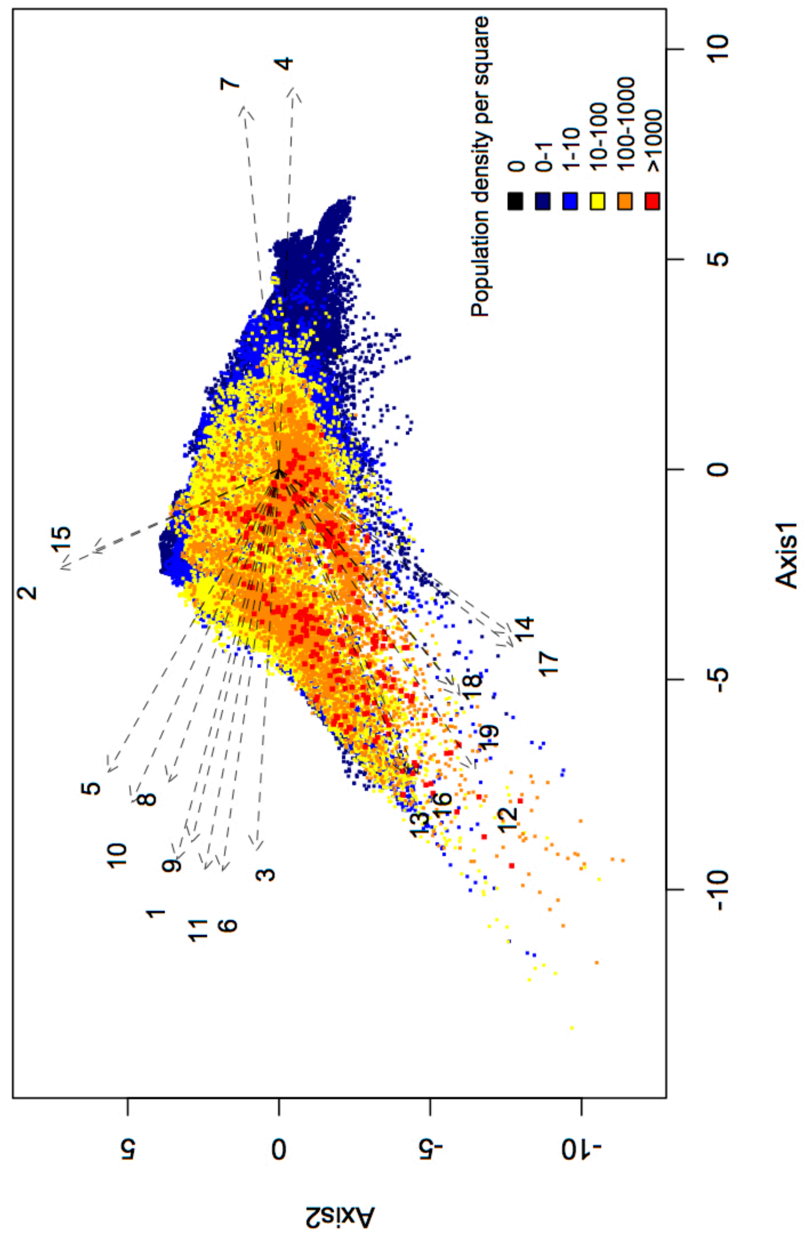
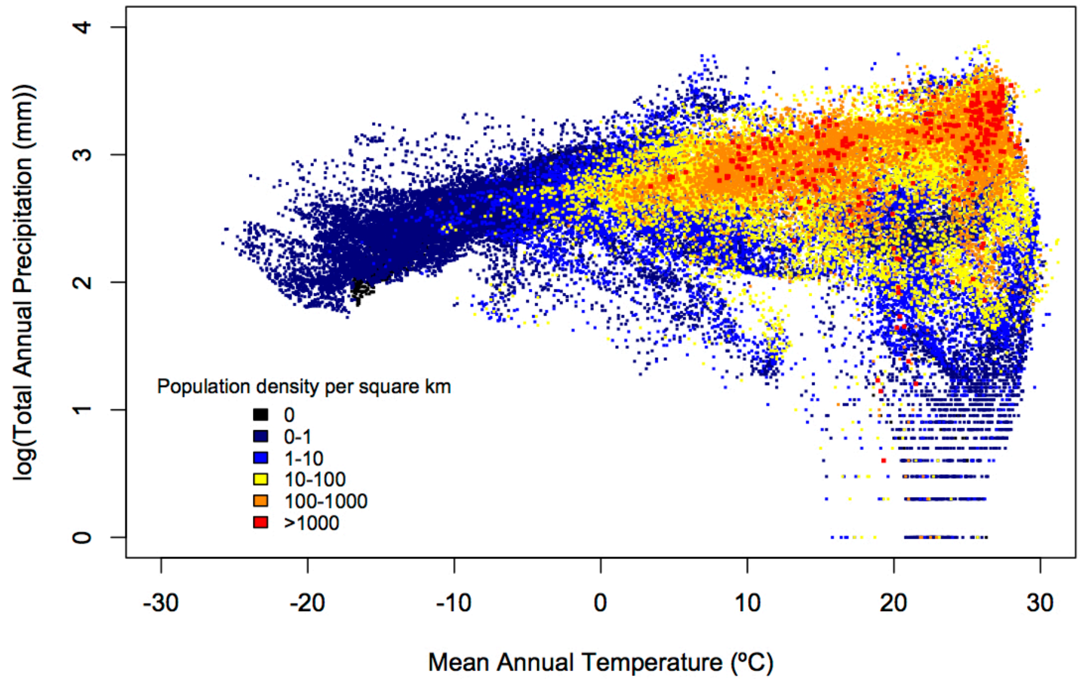


Figure 2.1: Global climate space constructed from 19 climate variables using Principal Components Analysis. Origin indicates global climate mean. Arrows shown are the direction of each climate factor's influence on the space, the number corresponds to the climate variable as listed in Table 2.1. Also shown are the population density categories from 0 people per square kilometre (NoPop) to more than 1000 people per square kilometre (VHighPop). Each point represents one 0.5° grid-cell.

a)



b)

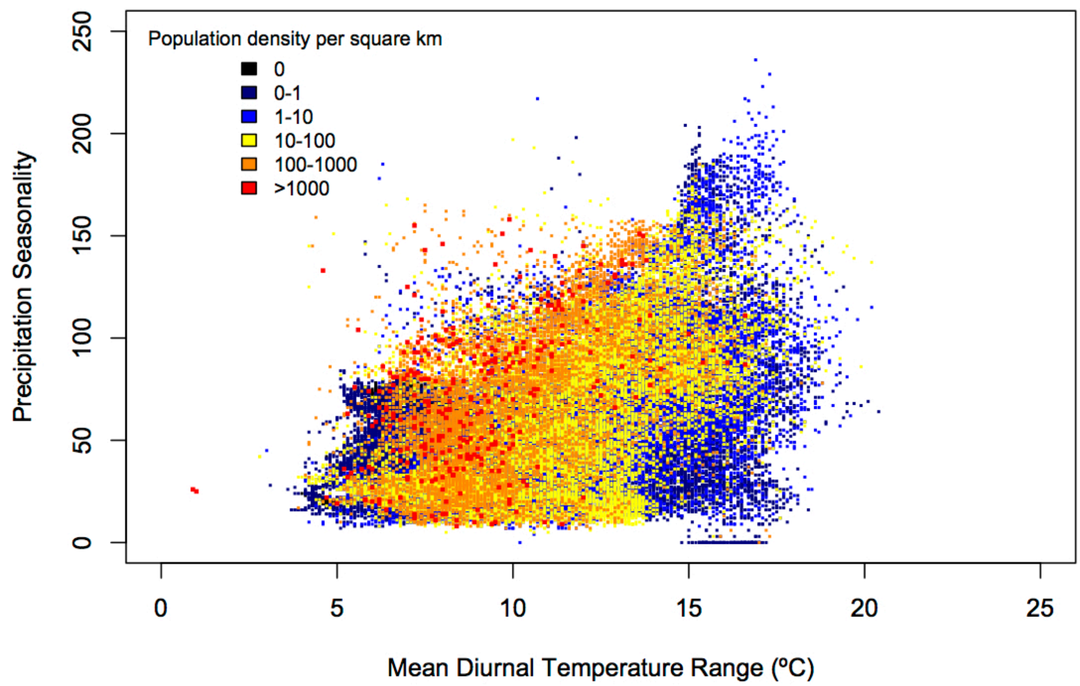


Figure 2.2: 4 key factors of global climate space shown independently with human population density grid cells: a) : mean annual temperature (ºC) and log_{10} of total annual rainfall (mm); b: mean diurnal temperature range (ºC) and precipitation seasonality (coefficient of variation). Each point represents one 0.5º grid-cell.

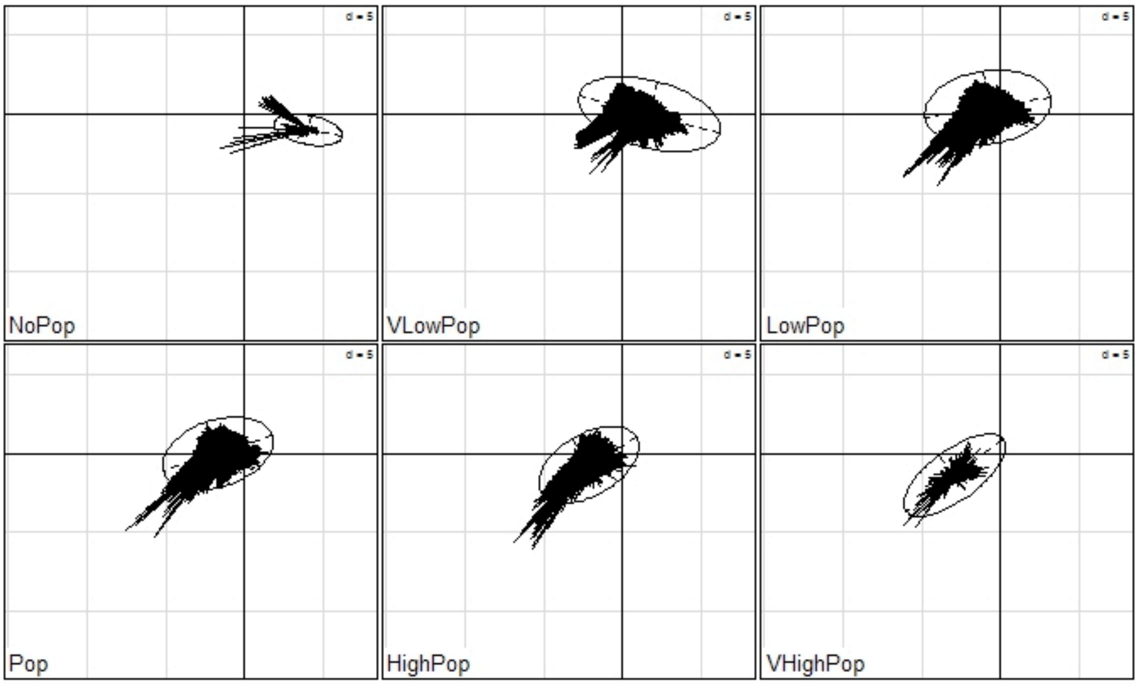


Figure 2.3: The positions of each population category in global climate space, calculated using Outlying Mean Index (OMI) (Table 2.2). Shown are the calculated niches (ellipses) for each population category and their outlying points (cstar=0.5). Origin is global mean of all climate space variables. The centre of each niche represents the OMI value and the size of the niche is determined by its tolerance.

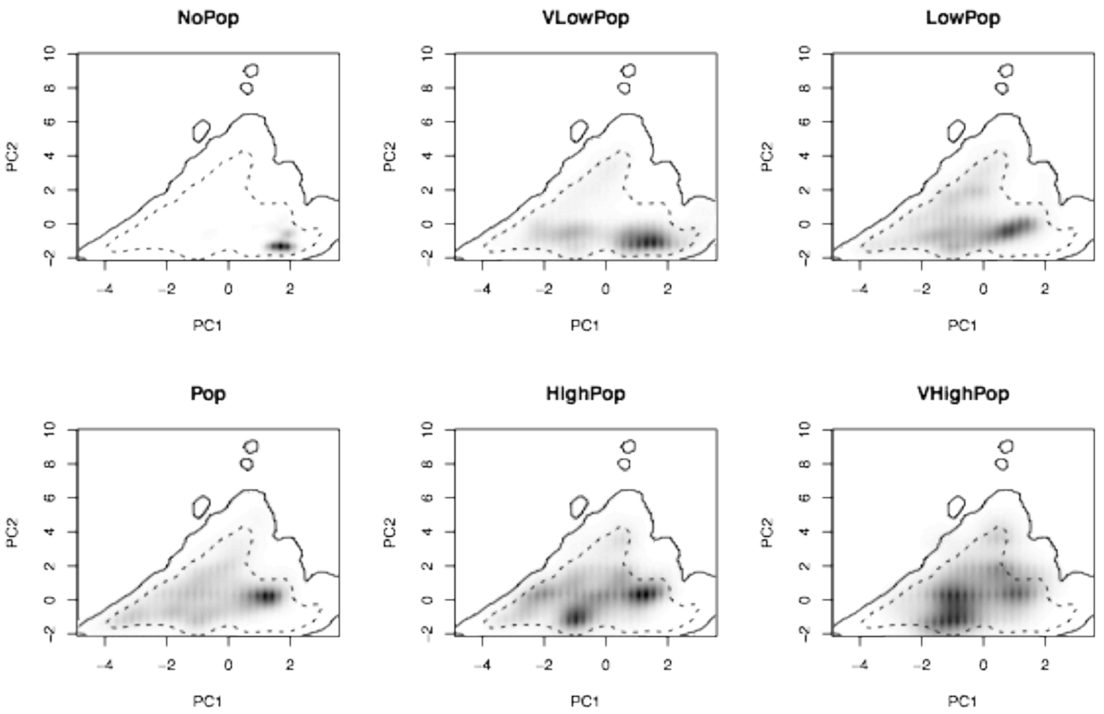


Figure 2.4: Density distribution of grid cells of each population category within global climate space, used to calculate D statistic (Table 2.3). Axes are principal components axes calculated by PCA for all 19 climate variables. Global climate space outline is shown by solid line (taken from Fig. 2.1), 50% margin by the dotted. Shading indicates grid cell distribution and density for each population category within climate space. NB: climate space is mirrored compared to previous figures along x axis.

Discussion:

We are interested in the utilisation of climate space by the human population as a whole. That is, within the full range of climate variables available on planet Earth, where are high population densities likely to be found. Studies in human geography suggest climate is a large-scale predictor of human dispersal, as it is for most other organisms. We found that although there is evidence to suggest links of human population dispersal to climate, the utilisation of it is regionally variable. High population densities do occupy different areas of climate space to low densities, though there is significant overlap (Table 2.3; Fig. 2.4). Populations associated with temperate or arctic conditions show a general trend of lower population density as the climate becomes more marginal (i.e. extreme) (Table 2.2; Fig. 2.1-2.3). In central climate space both medium and high density populations are present with some variation in a unimodal fashion (Table 2.2; Fig. 2.1). Finally, and against expectations, high density populations were found on average to be more marginal and at the upper end of climate space (Table 2.2; Fig. 2.1). This was found to be associated with tropical areas of the Earth. Both low and high population densities were associated with many tropical areas, possibly indicating some disequilibrium of population with climate, probably linked to sociological factors as well as historical resource availability, local geography, proximity to fresh water or the sea, existing or potential trade routes and finally some quantity of random chance. The reasons for why these high density populations are able to exist at the edge of current climate space are important, as rapid climate change is more likely to negatively affect these areas. This forms a basis for future investigation.

How are human populations distributed across global climate space?

A randomly spread population would show uniform population densities across the globe, and would indicate population density is not determined by climate variables. Empirically we know polar and desert regions are less heavily populated, so it would be unlikely that this result would appear. Typically in other species, the most heavily populated areas of niches are defined as the centre of their inhabited climate space (Huntley, 1995; Pearson *et al.*, 2002), though this is not always the case, for example if there is a determining nutrient threshold but not an upper limit (e.g. Pearson *et al.*, 2002; Pederson & Borum, 1996). As such we typically expect central climate space, as determined by all environmental factors, to be most densely populated. By separating the full range of human population densities into a categorical logarithmic scale ordination analysis can be carried out to investigate this question.

Ordination analysis has the advantage of considering multiple climate variables simultaneously and compressing them for graphical representation. Typically ordination analysis is used as a rough guide to allow graphical comparison between relative similarity of niches, however recently quantification and even statistical analysis of niche overlap has emerged (Broennimann *et al*., 2012; Warren *et al.*, 2008). The niches for individual population categories are shown as calculated by the OMI and can be compared both against each other and the global mean (Table 2.2; Fig. 2.3). The medium to low population densities (10-100 people per km^2) appear most centralised in climate space (lowest OMI, Table 2.2). Lower population density categories are more marginalised, as expected as the climate becomes more extreme, but higher populations also become increasingly marginalised. This is more unusual as it would be expected that as larger populations require more resources and they would tend towards the more suitable areas represented by the central climate space away from extreme climates, a pattern often found in other organisms (Basille *et al.*, 2008; Huntley, 1995; Pearson *et al.*, 2002). That high population densities are found more towards the edge of available climate space, indicates either human spread disassociated with climate or an indication of unstable populations at the edge of climate space. One possibility is inadequate compensation for weighting in the niche analysis, since the medium population categories are larger than the marginal ones, thus weighting the mean climate space towards the central categories. However, more likely there are other factors at work not considered so far that explain this pattern. To further analysis a synthesis has to be taken between the mathematical results, the direct comparative figures and where climate space grid cells are actually placed within the real world. The position of grid cells in climate space is informative but the translation to their actual placement in the world offers more information on climate and human linkage.

What are the climate characteristics of regions with low/medium/high population densities?

It seems likely after comparison that the bias is towards the higher temperature and precipitation gradients, i.e. the tropics, where both high and low population densities exist. As the converse it seems temperate or arctic areas show a more consistent trend towards decreasing population as conditions become more marginal (i.e. extreme). The high tolerance of low populations indicates low populations are present throughout climate space (Table 2.2; Fig. 2.4). Combined with our initial graphical breakdown it seems that while central climate space has consistently medium to high population densities, associated with temperate and sub-tropical regions, the space described by the tropics in climate space has both low and high population densities present, in something of a bimodal distribution. This could be due to a breakdown in the link between humans and climate and other sociological factors may be at play, for example regional GDP which would allow large societies to form in inhospitable areas. Another potential issue is that a measure of realised niche using population data, such we have used here, assumes a population at equilibrium with current climate and one that is ideally spread, which can create problems in producing accurate models from data (Pearson & Dawson, 2003).

What is the marginality of and the overlap between regions with different population densities in global climate space?

Another way to clarify if there is a pattern to population distribution in climate space is to analyse the category separation. So far we have only considered each category's position and size relative to each other. Another useful method of analysis is to consider how much they overlap, a 100% overlap between population categories would indicate no difference between any of them, and 0% would mean they are entirely distinct. Niche overlap analysis is a commonly used method to determine species and population separation, and is used in this case to confirm that population categories are distinct from each other in climate space. Since the category boundaries chosen were arbitrary it was expected that there will be a great degree of overlap, and indeed there was between neighbouring categories (Table 2.3). When comparing overlap between low population and high populations densities the results show a much lower proportion of overlap (Table 2.3). High density populations are found in distinctly different areas of the climate space to low density populations despite their overlap. This adds evidence to suggest that climate factors can be used to predict population spread and by establishing this we allow conclusions about our marginality to be partially verified. It seems the high population band visible in Figure 2.1 at the very edge of the available climate space is part of a larger pattern of marginality of high population densities.

This investigation has several implications, most strongly in the context of climate change. While the risks of climate change are increasingly being explored (IPCC, 2007a), there is a growing need to identify an index of risk for areas to be able to create an appropriate response strategy to the risk climate change poses (Harmeling, 2008; IPCC 2007a). Marginal populations, ones that exist at the edge of inhabitable climate space, are more likely to be at risk in periods of change, a pattern shown in other species (Ohlemüller *et al*., 2008; Thuiller *et al*., 2005). A key question asked during this analysis was how marginal or centrally clustered are humans in climate space and a logical continuation to this would present the risks to populations at the edge of this space. Are marginal populations in fact more at risk from rapid climate change? What areas of inhabitable climate space are likely to disappear in the future, and are we 'running out of climate space' (Ohlemüller, 2011)? Chapter 3 will discuss the future changes to global climate space, and extend the current links found between human population and climate in the present into the future.

Informed by these conclusions a plan can be formed for further investigation. It has been identified that human populations today are variable in density and this variation is partly explained by climate; high and low population densities occupy different, though overlapping, portions of climate space. If this is the case then climate space can be to projected forwards into scenarios of climate change and linked to human population effects and risk. The effect of marginality of a population on risk from climate change will be explored and linked on a geographic basis to create a broad risk-assessment for both areas of climate space and of geographic space.

Conclusions

Quantifying and depicting the climate space of an organism is a useful method to investigate links between organisms and climate. As with other species, we found that human population distribution is strongly, but not absolutely, affected by climate, and is strongly affected by temperature and precipitation variables. Areas of climate space associated with arctic areas become less inhabited as the conditions become more extreme. Towards the centre of climate space, temperate to sub-tropical regions, human density is variable, but unimodally distributed around medium population densities. At the upper temperature and precipitation limits of climate space, typically tropical areas, both very high and very low densities were present in a bimodal fashion. This went against the original assumption that humans would be distributed most in the centre of their distribution range and global climate space. It appears that large high population density areas in tropical regions are more common than in temperate ones and exist right up until the edge of existing climate space.

Chapter 3: Measures of climate change in human climate space

Abstract

Background: With the increasing likelihood of rapid anthropogenic climate change the risk presented to human populations is considerable. High magnitudes of local climate present a high risk to ecological and human systems, as well as the development of unprecedented novel and extinct climates.
Methods: In this chapter future climate spaces are constructed using climate projections from several institutes and for various emission scenarios for the next 50 years. Using a previously constructed present-day climate space, we compare the relative levels of local climate change across the world, and track the movement and development of novel and extinct climates.
Findings: We find that many marginal areas of climate space will undergo the most rapid climate change and have a higher probability of developing novel or extinct climate. In total up to 15% of the Earth's surface may demonstrate novel or extinct climates in the next 50 years. The results are also linked to population density and many populous areas are also those most likely to develop high levels of climate change risk, including many cities in densely populated areas of Bangladesh, China, Malaysia and Indonesia. Other populated areas in central and sub-Saharan Africa, South America and New Zealand are also likely to become more at risk.
Conclusion: High levels of climate change are present on every continent. Key human populated areas are likely to be heavily affected by high magnitudes of climate change and by the development of novel and extinct climate.

Introduction

Measuring climate change and the risk associated with it can be difficult concepts to quantify. Climate change is not, and will not be, homogenous and some areas will be exposed to greater levels of change than others. When speaking on the consequences of climate change, change is typically measured using a mean global or continent-wide scale, such as in international reports such as the IPCC climate assessment (IPCC, 2007a). While global reports are useful and global rises in climate variables, such as temperature, do provide good indicators of the progression of climate change as a whole (IPCC, 2007a), it is unsatisfactory for regional climate change assessment and there is a need for analysis of climate change at a more local level. The emergence of regional climate models provide much needed regional risk assessment using downscaled data on gridded landscapes (Anyah & Semazzi, 2004; Arnell *et al*, 2005; Ekstrom *et* al, 2007; Kumar *et al.*, 2006). Measuring the regional levels of climate change and its effects on local ecosystems and species niches' is a commonly used approach in conservation and risk assessment (Broenimann *et al*., 2007; Daly *et al*., 2008; Diamond *et al*., 2012; Heubes *et al*., 2011; Loiselle *et al*., 2010; Pearson *et al*., 2007). However, the speed and severity of climate change in a region is not the only way to consider climate change. Measuring the difference between temperature values at a point is useful but does not necessarily include all information about effects on other climate factors and the nature of climate change as a whole. Here, we examine other methods of quantifying climate change by use of a global climate space (see Ch. 2).

Climate Change Distance

Climate change is likely to affect many of Earth's ecosystems and species. There is evidence that responses to increasing temperature and changing climate are already occurring in some species, especially those that live in extreme climates, such as the Arctic or mountainous regions (Chen *et al*., 2011; Franco *et al.*, 2006; Parmesan *et al*., 2006; Pounds *et al.*, 1999). While changes that have already occurred can be correlated to climatic changes to determine the nature of responses, projecting into the future is more complex. It is never certain exactly how the climate will change, and multiple predictive climate models are often used to produce a mean projection (IPCC, 2007a). Furthermore, a species' response to any climate change is also often unknown, it is often assumed that species will track their existing climate as it moves, for example, northwards or uphill to follow the temperature gradient. If this is not possible the likely outcome is an inability to compete resulting in population decreases or extinction. The possibility of such extinction events is one of the major concerns of environmental and conservation planning. In order to model species' response it is necessary to understand the links between climate and species distribution and to accurately measure climate change. Measuring climate change is not as simple as taking global, or even gridded statistics, there are multiple variables of precipitation, temperature and seasonality that control ecosystem functioning, that are not easily comparable or measurable in terms of species distribution.

Using extrapolation from existing weather data, climate data can be gridded to the Earth's surface and used to develop measures of climate change (Loarie *et al.,* 2009*;* Saxon *et al*., 2006). With projected climate simulations, statements can be made about how an area is likely to change in a given period of time in any climate variable. Projections from these models try to estimate how the climate will change from projected global warming due to the increase in greenhouse gas in the atmosphere (IPCC, 2007a). It is rare that climate variables are treated in isolation as there are feed-back links between them and their effects on species distribution is complex. One way to overcome this is to construct a species climate niche, or climate space, out of multiple relevant climate variables.

Within climate space several measures of climate change that encompass multiple climate variables can be introduced. One of the most intuitive measures of climate change as risk is a local measure of the degree or speed of change an area will undergo in the future. The more rapid climate change an area undergoes, the more unpredictable and potentially detrimental the effects are likely to be to the existing ecosystem and human population within the area.

Novel and Extinct Climate Change

One of the most difficult tasks in climate modelling is to continue to give accurate predictions when climate systems begin to operate in ways that have no analogue in the present day. A climate that emerges of either a more extreme nature or of a new combination of climate factors is defined as novel. Climate is simulated using present-day data and the emergence of wholly novel climate and the disappearance of climates that many species and societies rely upon represent areas in the future of the highest risk and most unpredictable responses (Ackerley *et al*., 2010; Williams *et al.,* 2007). Novel climates present increased possibilities for extreme weather events, unknown ecosystem responses, changes in disease functioning and direct effects on human health (Hobbs *et al*., 2006; Patz *et al*., 2005; Williams *et al*., 2007). The more extreme or rare a climate is in the present day the more risk it faces of becoming extinct from climate change (Ohlemüller *et al.* 2008). The more extreme a region becomes in the future the more extreme the climate conditions within it become, and therefore the more likely it is to change rapidly, and develop novel or extinct climate space in the future with corresponding ecological impacts (Erasmus *et al*., 2002; Swihart *et al*., 2002; Thruiller *et al*., 2005).

In the past, extinction of climates has represented significant reduction or extinction of ecosystems associated with that climate, and it is reasonable to assume the same may be true in the future (Alley *et al*., 2003; Crowley & North, 1988). Paleoecological records suggest that species community assemblages that do not exist today most likely developed in many cases in non-analogue climates that now do not exist (Jackson & Williams, 2004, Williams *et al*., 2007). Novel climate in the future, in conjunction with human land-use and agriculture, biological responses and migrations, and changes in climate, is likely to be of concern to the human population (Hobbs *et al.*, 2006).

Population and Climate Change

The responses to climate change by humans are no less likely to be drastic than that of species and ecosystems. The multitude of risks faced by mankind globally have been discussed in depth in many fields (IPCC, 2007a), such as the potential population risk from sea-level rises, extreme weather-events, agricultural impacts and disease spread. The many risks humans are likely to face from climate change are driven by anthropogenic carbon emissions and subsequent temperature rises. While some effects will not be created locally, for example sea-level rise in the Indian Ocean is more likely to be driven by temperature increases in the Arctic than locally, many risks faced are determined by the level of climate change faced regionally. The higher the level of change experienced, the more rapidly a community needs to respond. Climate change and risk to populations are linked partly by how human infrastructure is built to cope within certain climate parameters, but more so in that human spread is strongly linked to agriculture.

Correlating human populations to climate is difficult, but previous investigations have found evidence to link climate change and population trends (Samson *et al*., 2006). This suggestion is supported by previous results that suggest that areas with different population densities can be found in distinct areas of the global climate space (see Ch. 2), with many high-density populations present in very marginal climate space (corresponding typically to areas of south-east Asia). Population density has been included to explore the possibility of links and patterns between climate change and population risk.

As potential risk to populations is a primary factor in decisions to mitigate climate change, risk in areas of high population density are of more immediate and pressing concern than if they were sparsely populated, and development of novel or extinct climate in populous areas would also be of concern to future international planning.

This chapter has two principal aims; Firstly, to quantify and map three components of climate change exposure a location might experience between now and 2050; secondly to analyse the relationship between human population density and these three measures of climate change exposure. To this end there are four objectives to this chapter:

1) To quantify and map the rate of climate change expressed as the distance between current and future climate conditions in multidimensional climate space.
2) To quantify and map the degree to which a location will experience novel or disappearing climatic conditions in the future.
3) To quantify and map the degree to which the climate of a location will become more or less marginal by 2050 expressed as the direction in which climate conditions move in climate space either to or from global mean conditions.
4) To analyse how these three components of climate change exposure change along a gradient of low to high population density.

Methods

Data

Present-day gridded climate data came from the WorldClim bioclim database at 10' resolution (Hijmans *et al*., 2005). Future data came from an associated data source; CIAT data for all emissions and models for the 2050 time slice (Ramirez & Jarvis, 2008). Both datasets are produced using interpolation to create high-resolution grids from climate output and as CIAT data are standardised against the Worldclim database the values are directly comparable. Population data were downloaded from CIESIN using the adjusted GPW3 dataset (CIESIN, 2005). The data were aggregated by mean to 0.5° (approx. 55km) grid cells. Two main emissions scenarios were compared, one low/mid-line and one high (A1B and A2 respectively), for various climate model outputs. HadCM3 A1B output is used as the standard in the results, and is compared to its corresponding A2 output, and to CGCM3 model output. While other models were investigated they are for the most part not presented here as the data downloaded from CIAT lacked data for points above 60 degrees latitude, making consistent comparison difficult.

Constructing a Climate Space

A climate space is a method of analysing multiple factors simultaneously and plotting them in two dimensions. The concept of climate space forms the basis of analysing global climate change in this chapter, as it has in several other analyses (Ohlemüller *et al*., 2006; Saxon *et al*., 2006; Williams *et al*., 2007). Using principal components analysis (PCA) 19 climate variables were summarised into two axes and were used to quantify the current and future position of each grid cell in a multivariate climate space, see Chapter 2 for a more detailed explanation of climate space construction. Analysis was carried out using the *ade4* package in R, using the present as the baseline for all emission scenarios and climate models, producing comparable paired datasets of present and future points in climate space in two axes which explain 53% and 24% of total climate variation respectively (a third adds an additional 7%).

Distance and Directional Change

Distance between corresponding grid cells of current and future conditions in climate space was calculated using the Euclidean distance between the axes values of each point: $\sqrt{((\mathbf{q_i}-\mathbf{p_i})^2)}$, where **q** is the position of a grid cell in the present-day data set and **p** is the position of that same grid cell in climate space in the future dataset.. A measure of marginality change was included by comparing the distance from the mean between the present and future for every pair of ordination grid cells. The difference between these two figures indicates the distance travelled to or from the global mean, positive meaning away (i.e. that grid cell becomes more marginal) and negative towards the global mean.

Novel and Extinct Space

It can be difficult to define exactly what qualifies as novel and extinct climate, as while stating an area will be hotter than ever before is an important observation, it does not take into account the many variables that help determine and regulate an ecosystem's functioning. By incorporating multiple climate factors at once in a constructed 'climate space' that models all ecologically relevant climate variables, we can include measure of novelty and extinction of climate. Using this method a point that exists outside of a constructed climate space can be said to be 'novel' and a point that exists in climate space at present but does not in the future is 'extinct'.

Novel space was calculated using a subset search tool which identifies points that occupy locations in future climate space that have no analogue in present-day climate space and therefore represent climates that may exist in the future that have no equivalent in the present day. A measure of novelty was created corresponding to the degree of rounding of PCA axis values necessary to force future gridcell values to overlap with a gridcell in the present dataset. If a gridcell in the future overlaps or coexists with a present-day gridcell it is considered non-novel. If a small degree of rounding is necessary to cause coexistence of gridcells in climate space it is considered slightly novel, and if even large amounts of rounding (in this case to the nearest whole integer) do not cause overlapping gridcells the gridcell is considered wholly novel. The levels of novelty calculated ranged from no rounding necessary which indicates no novelty, rounded to one decimal point, rounded to the nearest 0.25, to the nearest 0.5 and rounded to the nearest integer, indicating an extremely novel climate in the future. Extinct space was calculated as the inverse, points that exist in the present but not the future with a similar measure of severity gradient.

Population Analysis

For each of these climate change analyses summary statistics of both global and population categories were calculated to show gradients in climate change not just across geographical area but across population density. Population density is separated into distinct categories and defined with population density boundaries of 0, 0-1, 1-10, 10-100, 100-1000 and >1000 people per square kilometre, labelled as 'NoPop', 'VLowPop', 'LowPop', 'Pop', 'HighPop' and 'VHighPop' respectively (more details on population categories can be found in Ch. 2 methods). Population categories are separated in climate space and the averages for each climate change metric within each category are shown; these include the climate change distance and average change in marginality within a category, the percentage of novel and extinct areas and the proportion of areas with increased marginality.

Results

Distance

There is a great deal of variability in the extent and nature of climate change across the world. Figure 2.1 maps the distance between points in the present and their corresponding position in climate space in the future. Blue to dark blue corresponds to areas that will experience very little change in any way in the next 50 years, which is common in Eastern Europe, the US, Southern Australia and the Sahara. In contrast, areas such as South-East Asia, the north of the Amazon, the north of Greenland and Siberia and Southern Europe will undergo rapid change within climate space (Fig. 2.1). While the sub-Sahara will develop novel climate (Fig. 2.2), it does not appear to undergo rapid climate change under any model.

As expected, there is significantly more change in the A2 scenario, though this is by no means true universally, HadCM3 A1b provided some of the lowest and highest projection for climate change. In general the extent, severity and degree of climate change is greatest in the CGCM3 A2 scenario as measured by distance, although it is not scaled linearly from A1b to A2. The worst affected areas do not show significantly more change in CGCM3 models, but areas that in previous models show modest amounts of change display much higher levels of climate change. There is a general trend that a higher mean climate change does not significantly affect the most at-risk areas, but instead translates to an increase in the minimum level of change experienced elsewhere. Interestingly, although HadCM3 generally shows lower levels of climate on average in most regions, it does contain some of the highest distances measured between two points, notably in South America and South-East Asia. Elsewhere, especially in Arctic and sub-Arctic areas it shows clearly lower levels of climate change than the HadCM3 A2 scenario. In climate space, while areas that tend towards the higher temperature edge of space show consistently high levels of change, it is in cooler climates (to the right of climate space (Fig. 2.1) where change is noticeably higher in higher emission scenarios.

Novel and Extinct Space

When comparing present and future climates, it is clear that some climates will appear in the future which have no current equivalent and some will disappear entirely. In an attempt to clarify where these novel and extinct climates will occur, we used simple isolation analysis to create an index of novelty and extinction potential of points in climate space. The further away from any present point a future point is the more novel it is, indicating more rapid change, and the more likely it is to be wholly novel. Figure 3.2 clarifies this index and maps the novel points found in climate space onto a global map to show where climate change will create most novel conditions in the future. The gradient from dark to bright green corresponds to the degree of rounding necessary to force overlapping with a point from the present. This forms a measure of novelty with bright green being the most novel. In the geographic maps a grey measure is also included to show a buffer zone of novel points that are within 0.01 ordination points of being analogous to a present day climate. Of particular note are areas brightly highlighted in sub-Saharan Africa, the Amazon, the Himalayas, Greenland, New Zealand and South-East Asia.

The converse was carried out for extinct space. Points that currently exist in the present but have no analogue in the future even given rounding are considered to be extinct. Figure 3.3b shows this plotted in climate space and correspondingly on a global map. Areas of the southern Andes, Himalayas, Siberia, Greenland, New Zealand and the north of Canada all show climates that are likely to disappear in the next 50 years. South-East Asia also shows areas of extinct climate in similar areas to where novel climate will appear throughout Indonesia, Papua New Guinea and the island of Borneo. All models and emission scenarios show the same general areas of novel and extinct climate space, with some minor differences in distribution. For example, HadCM3 shows more major development of novel climate in the Amazon, but CGCM3 shows more wide-spread novelty in sub-Saharan Africa and less wide-spread extinct climate in northern Canada.

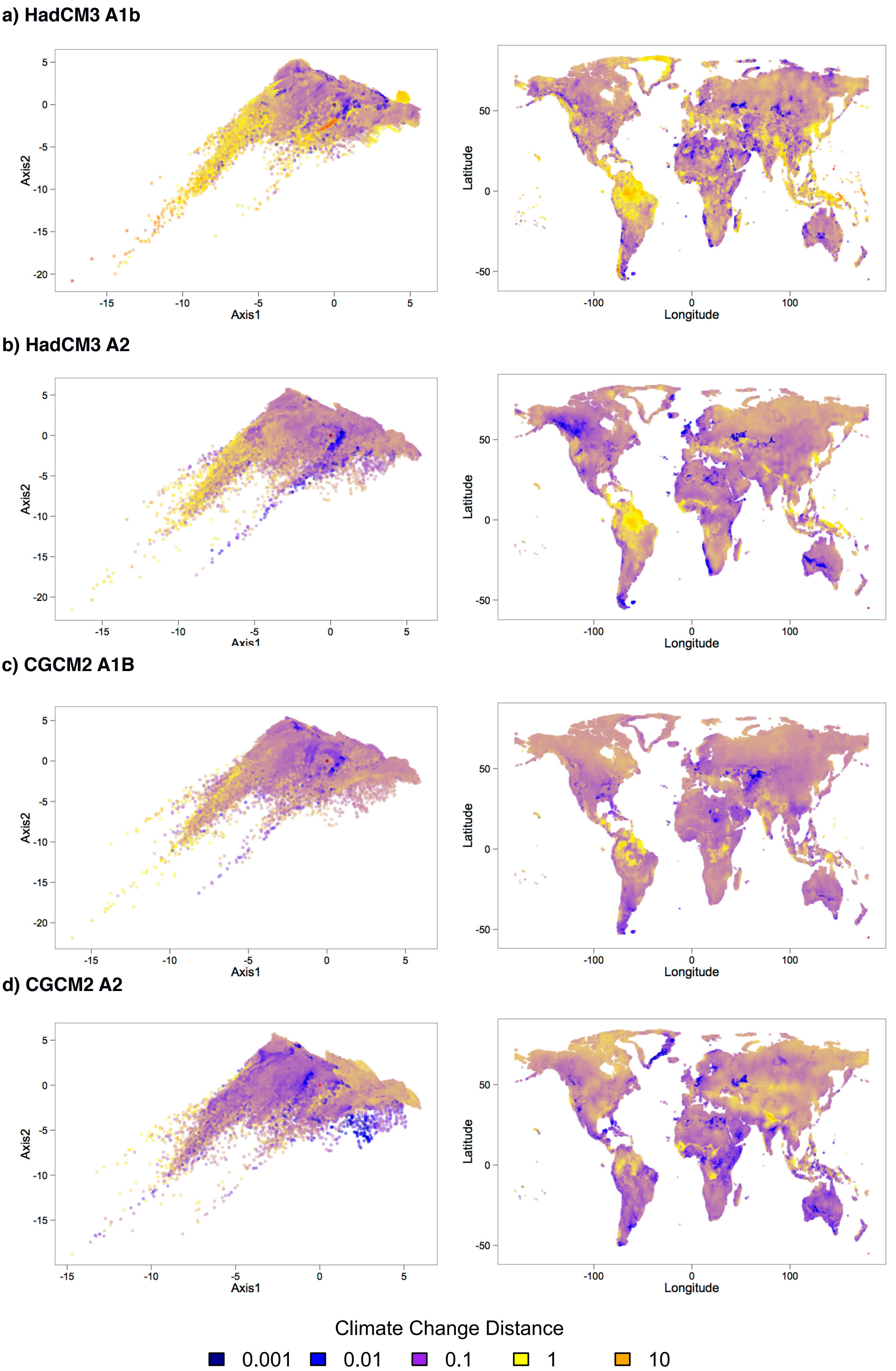
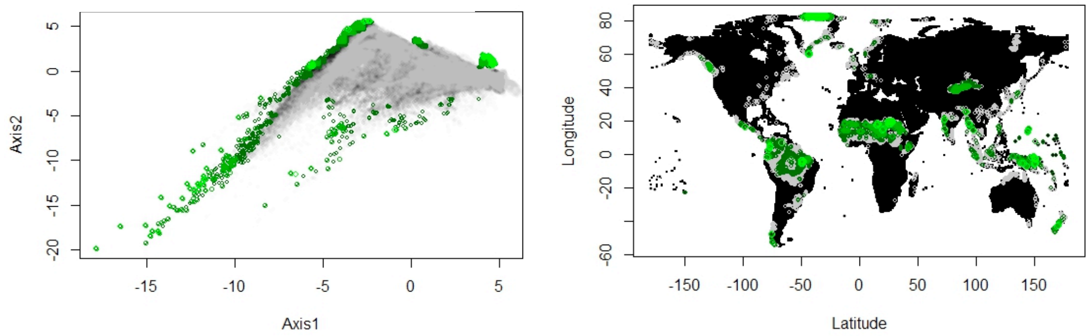
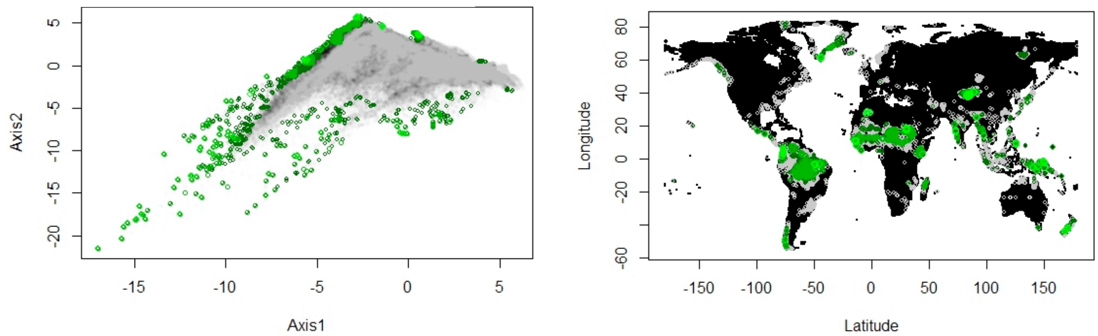


Figure 3.1: Magnitude of climate change shown as the distance in PCA ordination axes between current and future climate spaces plotted in ordination space (left) and geographic space (right) for two example climate models and two ghg emission scenarios in 2050. Colour gradient from blue to yellow with dark blue indicating very little climate change over the time period, and yellow and red indicating increasingly high levels of climate change.

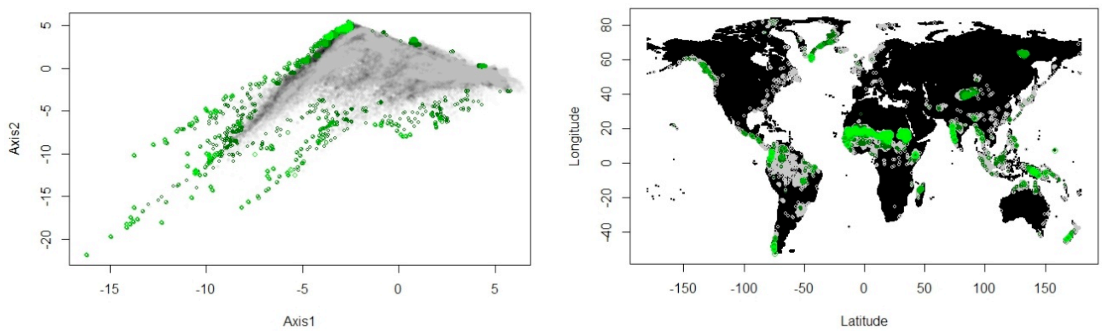
a) HadCM3 A1B



b) HadCM3 A2



c) CGCM3 A1B



d) CGCM3 A2

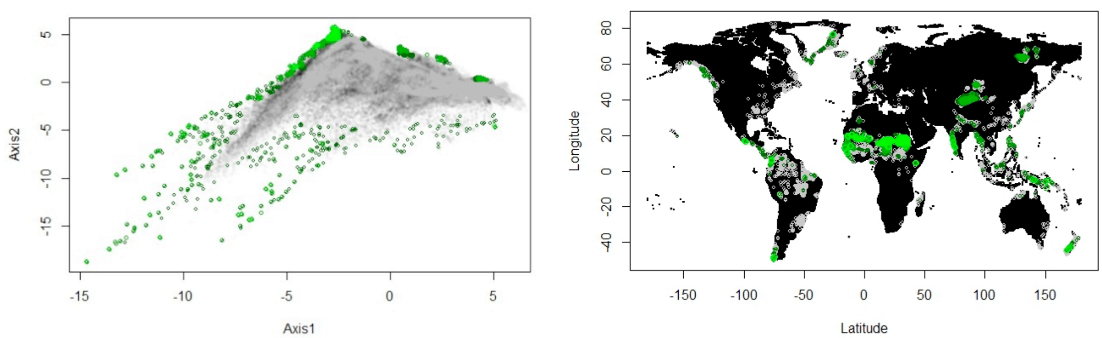
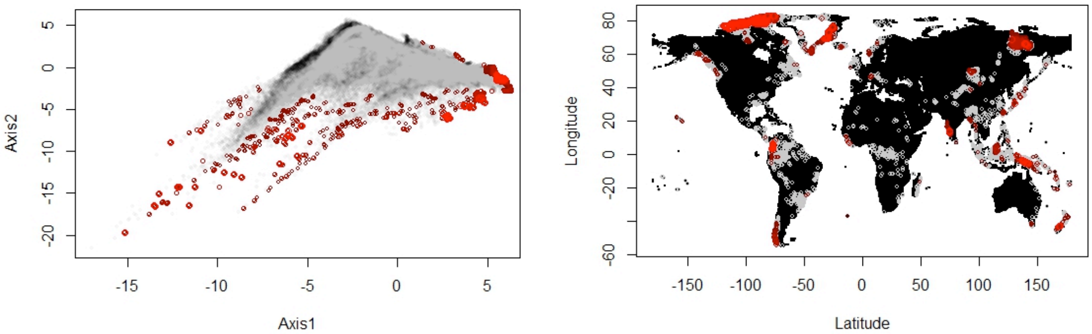
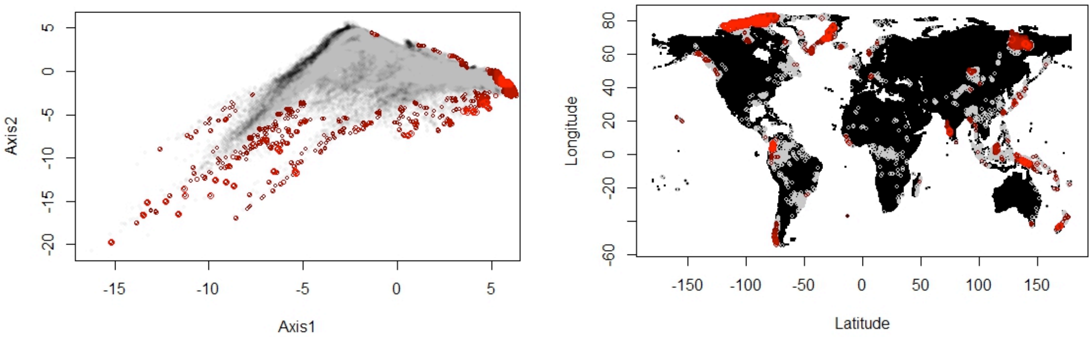


Figure 3.2: Map of novel climate space in ordination and geographical space. In ordination space black and grey correspond to 2050 and 2000 climate space respectively and green corresponds to level of confidence that a point is novel, brightest meaning most remote from all present points and dark green being closest. The same colour coding applies to the geographic maps on the right geographic maps; black points map land grid cells and the grey to green gradient maps novelty of points with novel climate in the same way as in ordination space.

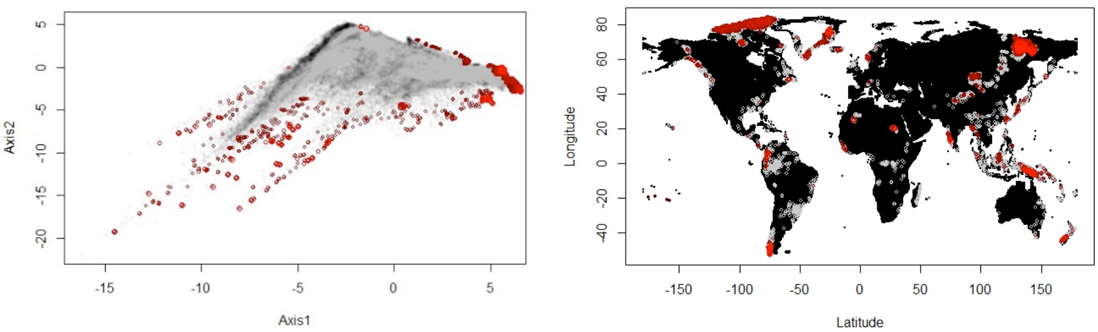
a) HadCM3 A1B



b) HadCM3 A2



c) CGCM2 A1B



d) CGCM2 A2

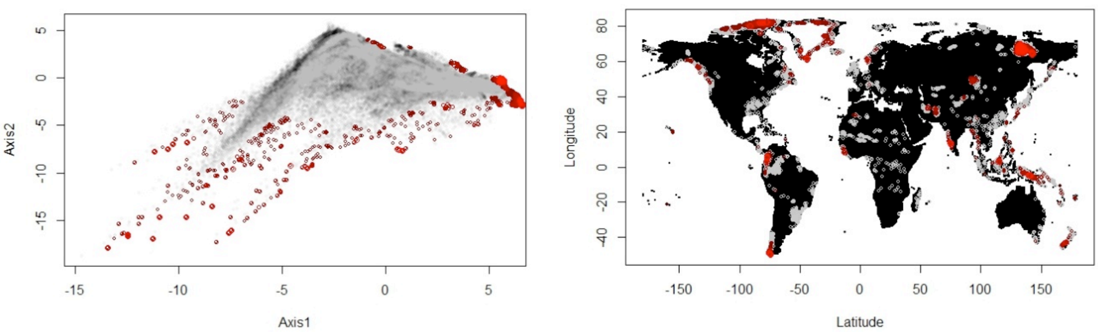


Figure 3.3: Map of extinct climate space in ordination and geographical space. In ordination space black and grey correspond to 2050 and 2000 climate space respectively and red corresponds to level of confidence that a point is extinct, brightest meaning most remote from all future points and dark green being closest. In the geographic map black points map land grid cells and the grey to red gradient maps likelihood of extinction in the same way as in ordination space.

Marginality Changes

Figure 3.4a illustrates both the shape of global climate space and how marginality varies across the world. Central climate space, the mean climate conditions determined by the mean of 19 climate variables, is distributed across temperate regions of the Earth, across the US, Europe, Eastern China, southern Australia and South America. In one direction, climate space becomes more marginal with lower temperatures and rainfall (to the right of central climate space, Fig. 3.4a. For details on which climate variables correspond to which directions in climate space see Ch. 2) which represents more extreme climate in northern Canada, Siberia and some mountainous regions. In the other direction (left of central climate space) more marginal space can be found with higher temperature and in regions with higher and lower rainfall. This corresponds to both tropical regions, such as in the Amazon, South-East Asia and central Africa, and desert regions, such as the Sahara, regions of the Middle East and Australia.

Marginality changes measure whether the movement of a grid cell in climate space will be towards or away from the global mean. Since on average climate space shifts in a general direction, corresponding to an increase in global average temperature, most points to the right of the global mean move towards the global mean, and most points to the left move away from the mean and become more marginal (Fig. 3.4b). Both past and future points are compared to the present global mean, which is approximately 0.05 units of climate space away from the future mean. As such, most points at high latitudes shift towards a global mean (Fig. 3.4b) and most points near the equator move away from the present mean. Some exceptions exist in mountainous areas, for example the whole Himalayan region shifts towards a warmer global mean. The areas to note are those that are the exception to these patterns, provided below for CGCM3 A1b (Fig. 3.4b), used as an example of marginality shifts in climate space and is very similar to patterns shown in other climate models. Areas labelled in white show particularly marginalised climate space. These include many areas, but not all, of South East Asia, sub-Saharan Africa and South America. The Himalayas also show pronounced shifts towards marginal climate, though this is more noticeable in other models. Perhaps surprisingly, given that the area has been shown to develop novel space and undergo rapid change in the future, areas around the north Amazon directly adjacent to increasingly marginal space show a clear trend towards the global mean. This is counter the trend for both equatorial latitudes and for the areas around it in South America.

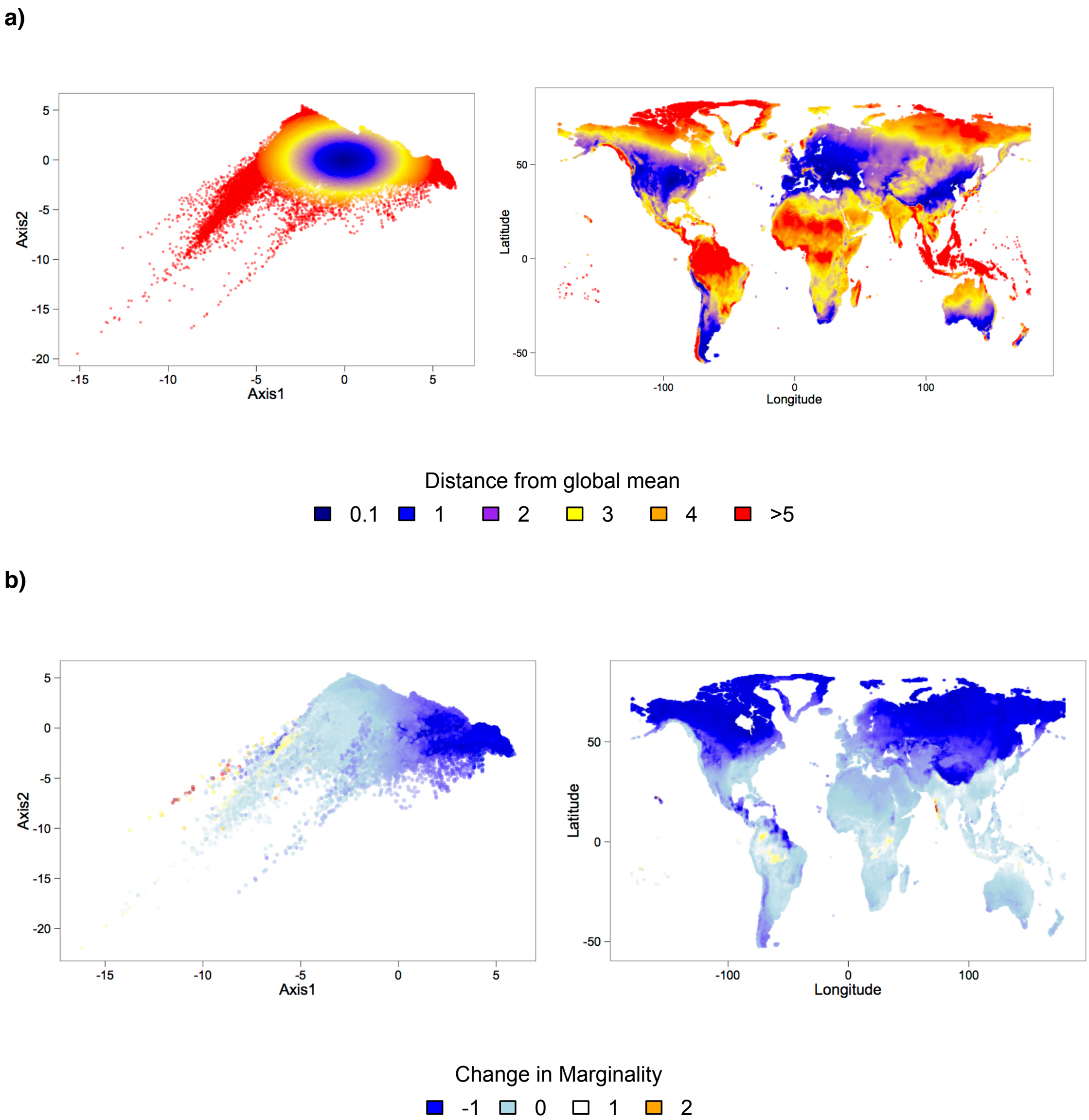


Figure 3.4: a) Climate space gradient expressed as the distance of each grid cell from the centre of climate space in the present-day 2000 dataset. Central climate space is labelled as dark blue and marginal climate space as red. This is then shown on a global map to illustrate what regions of the Earth are more or less central in climate space. b) Ordination and geographical map of change in position of each grid cell between 2000 and 2050 datasets. Dark blue indicates that a grid cell moves towards the global climate mean strongly in the future and paler blues away from it. White and yellow colours indicate strong movement from the mean towards marginal space in the future.

Climate Change Exposure and Human Population Densities

Possible trends between population size and climate space shifts were investigated using population categories and climate space. Any differences in the distribution of climate effects between population categories changes the way we interpret the effects of climate change on human populations.

Trends in climate change distance were mixed between population categories. The average for each category increases as population increases in HadCM3 models, but slightly decreases in CGCM3 (Table 3.1; Fig. 3.6). This could be attributed to differing assumptions and outcomes of the different climate models, though the reason why is difficult to attribute. Although differences are small given the variability of the data (Fig. 4.6), there is a significant link between a decrease in population category and an increase in its average climate distance in CGCM3 models (ANOVA, DF=~65000 (dependent on model), $P<0.01$ for all levels). A trend of increasing climate change distance with increasing population category is apparent in HadCM3 models, and analysis shows a significant link between the two but to a less convincing extent than the CGCM3 models.

Most regions, apart from those with a population of 0, show a reasonably consistent 10-20% proportion of novel climate in every population category and climate (Table 3.1). This means that in 50 years 10% of the Earth's surface will compose of currently non-existing climates, climates of which we have no experience of. Extinct climate is most common in low population categories, probably as extinct space corresponds mostly to uninhabited areas in Siberia and Canada (Fig. 3.4), but in higher population categories extinct space is still consistently 5% of all grid cells (Table 3.1). As a global average up to 10% of currently existing climates appear as extinct in the next 50 years according to this analysis.

Direction and marginality within population categories possessed clear trends of negative movement towards the mean for low population categories and positive movement (away from the mean) for higher population categories, regardless of model or emission scenario (Table 3.1). In a similar manner low population categories had a much lower proportion of points with increased marginality than higher population categories (Table 3.1). This trend was confirmed statistically suggesting a predictable link between population category and direction of movement in climate space (ANOVA, DF=~65000 (dependent on model), $p<0.05$ for all levels and models). High population grid-cells are much more likely to become more marginal in climate space in 50 years.

Table 3.1: The three climate change exposure measures for two climate models and two emissions scenarios; (**a)** average distance in climate space; **b)** proportion of area with novel and extinct climates; **c)** average change in marginality (+ve is away from mean, and -ve towards) and proportion of area with increased marginality in climate space) for each of six population density categories

a) Distance in climate space				
	HadCM3		**CGCM3**	
	A1B	**A2**	**A1B**	**A2**
NoPop	0.69	0.53	0.71	0.84
VLowPop	0.78	0.65	0.63	0.63
LowPop	0.8	0.64	0.56	0.57
Pop	0.83	0.64	0.56	0.58
HighPop	0.91	0.63	0.59	0.62
VHighPop	1.05	0.65	0.61	0.61

b) Novel and extinct climates								
	NOVEL climate				**EXTINCT climate**			
	HadCM3		**CGCM3**		**HadCM3**		**CGCM3**	
	A1B	**A2**	**A1B**	**A2**	**A1B**	**A2**	**A1B**	**A2**
NoPop	1%	0.5%	1%	0.3%	2%	7%	6%	3%
VLowPop	12%	11%	1%	7%	18%	14%	16%	13%
LowPop	19%	17%	16%	13%	8%	6%	6%	6%
Pop	15%	15%	14%	11%	8%	6%	5%	6%
HighPop	10%	10%	11%	9%	6%	6%	5%	6%
VHighPop	13%	13%	16%	12%	11%	9%	7%	8%
Global	**14%**	**13%**	**12%**	**9%**	**12%**	**9%**	**10%**	**9%**

c) Direction and marginality in climate space								
	Direction				**Marginality**			
	HadCM3		**CGCM3**		**HadCM3**		**CGCM3**	
	A1B	**A2**	**A1B**	**A2**	**A1B**	**A2**	**A1B**	**A2**
NoPop	-0.59	-0.44	-0.63	-0.67	3%	2%	3%	3%
VLowPop	-0.35	-0.33	-0.34	-0.36	26%	26%	28%	26%
LowPop	-0.05	-0.04	-0.04	-0.09	52%	53%	53%	52%
Pop	0.10	0.09	0.08	0.04	64%	66%	66%	63
HighPop	0.25	0.22	0.23	0.18	75%	79%	78%	75%
VHighPop	0.31	0.34	0.35	0.26	82%	89%	93%	86%

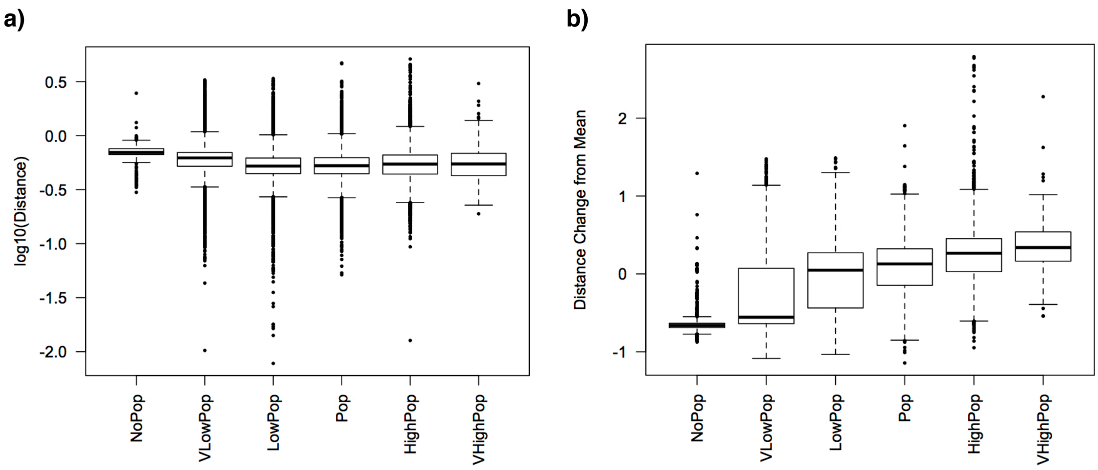


Figure 3.5: illustrated population categories for CGCM A1b as representative of general trends in other models for a) logged climate change distance and b) direction of movement. In the distance change boxplot, 0 is equivalent to no movement towards or away, negative numbers mean towards the global climate mean and positive away from the mean.

Discussion

Rapid climate change is frequently used to indicate increased risk as it equates to more drastic change, less time to adapt infrastructure and greater disruption to existing agricultural and natural ecosystems. Similarly, we here treated rapidity and extent of climate change in an area as risk and highlighted areas that are particularly prone to high and drastic changes. Areas that are likely to experience rapid climate change in the next 50 years include sub-Saharan Africa, the Amazon and South-East Asia. In addition, the development of novel and extinct climates were also noted as a particular risk. Novel climates will develop in similar areas of sub-Saharan Africa, the Amazon and South-East Asia, but also in Central America, the Himalayas, Greenland and New Zealand. These novel climates represent new combinations of climate factors that do not exist in the present day, and as such exist outside of current experience. Extinct climate space will also appear, in which combinations of climate variables that currently exist will cease to in the future. Areas where this is likely to occur include northern Canada, the Andes, and some areas of Siberia, south-east Asia and the Himalayas. Finally we present a metric of direction of climate change in multivariate space to suggest whether areas become more or less marginal. Combined, these measures of global climate change offer information on a changing world and indicators of not just global mean trends, but provide a rough index to what areas are going to undergo the most rapid and potentially dangerous climate change.

Global patterns of climate change exposure

The magnitude of climate change and the novelty of climate in a region are used as measures of risk for several reasons. Velocity of climate change is also a measure of severity, and is surprisingly variable over distance and patterns are very much local. Increased rate of climate change leaves less time for local infrastructure to adapt, greater chance of local mitigation being overwhelmed, greater chance of extreme events such as fires, droughts or flooding from sea-level or precipitation rises, and greater disruption to local ecosystems and human populations (IPCC, 2007a). By treating change on a more local scale we can measure the differential change in some areas versus another. Novel change is an extension to this argument; since current understanding of climate is primarily based around the current range of climatic conditions and combinations, the further we leave these boundaries behind the more unpredictable and possibly dangerous novel climate becomes (Williams & Jackson, 2007). In addition to the risks associated with rapid climate change, novel climate space has been suggested to lead to shifts in assemblages in species, leading to so-called 'no-analogue' communities (see Williams & Jackson, 2007). Similar arguments can be applied to areas of extinct climate space, as climates that are heading towards extinction present great risk of biodiversity loss (Ohlemüller *et al*., 2006). Points that move large distances in climate space are often reasonably approximate to the estimated areas produced by novel and extinct climate space analysis. Estimates vary depending on climate model and emission scenario, but particular areas of risk appear in both distance and novelty analyses in and around areas of tropical and mountainous ecosystems, especially in South-East Asia, South America and sub-Saharan Africa (Fig. 3.1; 3.2). Extinct space is also characterised by high levels of climate change, for example in New Zealand and Greenland (Fig. 3.1; 3.3).

Changes in marginality do not translate directly to risk as clearly as distance, but a grid cell that moves rapidly to more marginal climate space is more likely to experience more extreme climatic conditions and contain novel space. For example, South-East Asia is typified as moving rapidly towards more marginal space, caused by a projected drastic change in precipitation patterns and is likely to become much drier during key harvest times of the year (Naylor *et al*., 2006). It is also interesting to note how patterns of directional shift of climate space are variable even in points that seemingly have similar climate and inhabit roughly the same geographic location, see South America for example (Fig. 3.4). Similarly, points that are already marginal are more likely to move into space that is totally novel. Unusual climates are more at risk from extinction, simply by virtue of being unusual (Ohlemüller *et al*., 2008). Areas that are non-adjacent in climate space to any other similar climate (Fig. 3.4a) are especially prone to this. This is some confirmation that marginal populations and areas are more at risk from novel climate combinations and unpredictable climate patterns in the future. A note should be made however that these points that are separate from the majority of climate space are not above suspicion in terms of data observations. The collection of data, while interpolated well, relies upon the integrity of the input data. For many areas, such as North America and Europe, there exists many weather stations that provide very accurate fine-scale data, but for inaccessible regions, such as rainforests and deserts, there exist very few data observations and data for these grid-cells must be estimated. This reduces the power of any predictions based on this data, and may explain some strange outliers in the data which, for example, may belong to mountainous regions which often cause problems in interpolations in data due to sharp gradients in climate variables.

In this analysis multiple climate models and emission scenarios are compared. The aim is to compensate for any deviances in model type and function to find over-arching general trends in climate change magnitude and development of novel and extinct space. Due to some data constraints we did not include as many comparisons in the results as may be desirable, but across two models used (HadCM3 and CGCM3) results are comparable, with minor variations in degree and magnitude of change. Highlighted areas for change, direction and novel and extinct climates feature approximately the same areas (Fig. 3.1; 3.2; 3.3). The minor variations seen between models and emission scenarios are due to the different assumptions in circulation and climate processes in the original model. For example, HadCM3 is known to have slightly different assumptions and therefore slightly different predictions for precipitation patterns, especially in the Amazon basin. Surprisingly, between emissions scenarios there are only minor variations in distance and extent of novelty are visible. This is most likely due to the time-step used, chosen due to data availability at the time, since 2050 is a reasonably moderate time step. In the IPCC4 assessment (IPCC, 2007a) emission scenarios are non-divergent by 2050 and it is only by the end of the century that predictive models witness a significant divergence in CO_2 and temperature gradients. In analyses that look at this time-step divergences between emission scenarios are much more prominent (Williams *et al*., 2007). Having said that, there is some difference in the climate distance between A1B and A2 scenarios, which may be an early indication of differences between models, though this does not translate into a significant difference in the area of novel or extinct space.

Population and climate change exposure

A whole-scale change in ecosystem functioning could have disastrous consequences for populations that have adapted their life-style to a completely different type of climate. Since especially agricultural factors are highly linked to bioclimatic variables (Samson *et al*., 2011), a change in climate patterns could drastically affect rural populations. Urban populations are not exempt however, as previous natural disasters have shown how city infrastructure can be fragile when coping with environmental conditions outside of the norm, and it is to be expected that many more mitigation measures will be required in urban areas that undergo rapid climate change. Highly populated areas that undergo rapid climate change are more likely to encounter flooding, from sea-level rises or changing precipitation levels, fires, agricultural difficulties and other extreme events as current systems and infrastructure are less likely to compensate for rapid climate change. Areas where a high degree of climate shift and the possibility of novel climate space coincide should be especially noted as areas with a high degree of unpredictability and risk from climate change over the next century. It is likely that our estimates are conservative as to the impact novel climate will have on future systems.

Both the level of climate change and the direction of climate change were found to vary strongly across the investigated population categories. Interestingly, in terms of climate change distance, different models showed opposing trends; HadCM3 models showed a decrease in climate distance with increasing population density, and CGCM3 models showed an increasing trend (Table 3.1; Fig. 3.4b). When normalized and tested both of these differing trends proved significant. This may be due to the distributions of climate change across population centres in the different models, such as much higher levels of climate change in unpopulated areas such as Siberia in one model versus another, but it is uncertain why such opposing trends appear. Novel and extinct space in population categories show much clearer trends. They both increase significantly in higher population density categories (Table 3.1) and match trends for increasing marginality in higher population categories. This means that for two of the metrics used to consider climate change, higher population densities face consistently higher levels of risk. Population centres in South-East Asia, Africa and parts of Southern Europe appear particularly at risk.

Comparison with other methodological approaches

The areas highlighted here are not unheard of in previous risk assessments. Comparisons are sometimes difficult to make between varying methodologies, but a global risk index in whatever form can be used for some comparison. The most comparable analysis is that of Williams *et al.* (2007), who use standardised local climate change based on four key climate factors to form a metric of risk, and also look at novel and extinct climate space. They also include measures of biome 'tipping points' where they estimate that ecosystems will begin to collapse. Their results vary much more by emission scenario, most likely due to the larger time-step they use, but their metric of local change closely matches our results with the largest change being experienced across northern South America, sub-Saharan Africa and south-east Asia, though they show a greater extent of change across most of the Middle East. Their patterns of novel and extinct climate also show large similarities to our own results. Areas of the Amazon, Africa and south-east Asia as well as some sections of India will develop novel climate in comparable patterns to the results shown here, while extinct space will develop in the tip of South America, south-east Asia and some areas of Siberia. The distribution of extinct holds more dissimilarities than their novel space, with a greater extent along the Andes and some areas of central Africa. This separate example of climate change calculated from the same data is useful verification for our results. Samson *et al.* (2009) use a completely different methodology to produce a climate demographic vulnerability index (CDVI). It is interesting to note they also find similar regions of risk; namely the Amazon, South East Asia, sub-Saharan Africa and India, although they also predict high risks across the Middle East and their analysis has more gaps in the data set due to weather and demographic data deficiencies.

Other studies use a similar methodology to ours but for different purposes, typically on a more regional level. Ackerley *et al*. (2010) use similar multivariate analyses to characterise biome and conservation area changes in California. They include many of the same criteria for analysing climate change, including climate distance and the appearance of novel and extinct climate, but also include a measure of landscape heterogeneity to assess how this can act as a buffer to rapid climate change and conservation planning. Their work produces results in a similar format and logic to ours, but on a different scale of climate functioning. One aspect they also include is the concept of climates moving across a landscape, something that Loarie *et al*. (2005) expand upon and measure the rates specific climate combinations will move across a landscape and how rapidly ecosystems will have to move to match this pace. Saxon *et al*.'s approach (2005) may be described as most similar to the one carried out in this chapter and creates a multivariate space for the U.S. with the inclusion of some topographical measurements, which has the advantage of using very well defined fine-scale data within a well-studied and heterogenous area.Their additional level of analysis using topographical features is also a point that strongly affects population distribution and climate change, and proves significant in their analysis. Ideas from these studies allow a comparison of methodology and results, such as the repeated emergence of novel and extinct climate in all of these analyses where such patterns are looked for. As a whole the broad trends match here agree with their assessments, despite the varying methodologies.

The climate change factors used here to quantify climate change have a long history of usage in climate change ecology, and as such form a useful foundation for climate change risk analysis. As unique climate space disappears, species and communities that depend on those climatic conditions may suffer extinctions and/or re-shuffling of ranges and community assemblages (Hobbs *et al*., 2006; Jackson & Overpeck, 2000; Overpeck *et al*., 1992). The risk of novel climate space is supported by evidence from previous periods of rapid climate change, especially the last inter-glacial transition period in North America, during which many assemblages of even extant species were present in community combinations that no longer exist today (e.g. Jackson & Overpeck, 2000; Jackson & Williams, 2004; Mix *et al*., 1999; Morgan & Morgan 1980; Overpeck *et al*. 1992; Stafford *et al,*. 1999). Change does not happen uniformly and species do not respond simultaneously or linearly. In one of the last Holocene ice-age shifts novel climates quickly appeared and shifted across Europe, along with a wave of re-distribution of species ranges and extinctions (Davis & Shaw, 2002). Similarly, disappearing climate space means that certain extant climates will disappear entirely, possibly with whatever species that specialise in that climate, particularly if this climate is itself unusual (Ohlemüller *et al*., 2008). This has already been noted in mountainous areas as high-altitude species move uphill to follow the temperature gradient (Chen *et al*., 2011; Franco *et al*., 2006; Pounds *et al*., 1999). In Europe, several highland butterfly species are already facing extinction because of this (Franco *et al*., 2006; Hill *et al*., 2002), a pattern seen in disappearing mountainous climates across the globe (Franco *et al*., 2006; Thomas *et al*., 2006). The marginality and unusualness of climate are linked concepts, and climate associated with pre-warming conditions are already being tracked towards extinction (Ohlemüller *et al., 2006).* The concept of thresholds being key to ecosystem change has been explored before (Williams *et al*., 2007), and similar arguments apply to human systems. If a climate changes drastically but still has no comparable climate within 500 kilometres that does not help the population or species that encounter drastic climate change and no easy migration to similar climes. This approach is considered by Williams *et al.* (2007) by including a distance threshold around each future grid cell and if there exists no comparable climate to the focus cell's present climate conditions, it is considered functionally novel. We evade this slightly by including distance and direction of change, and consider distance to be an informative metric of risk.

The main difference in this methodology is the inclusion of multiple climate factors and the usage of a global climate space. Previous attempts have typically used four climate variables; usually mean annual temperature, total annual precipitation and a measure of the annual variability of these two, which are agreed to be good indicators of most other bioclimatic factors (Stephenson, 1998; Sitch *et al*., 2003) as they tend to be highly collinear. Multivariate space can take into account multiple factors simultaneously and can weight their change effects by their initial effect size and using all 19 variables captures a lot more subtlety in climate variation and change. Thus, collinear variables are partially made irrelevant and are masked by variables with stronger effect sizes, but still contribute a portion of axis power. The disadvantages of using a multivariate ordination system come from decoding the axes back into their individual components (e.g. trying to figure out what a point's given climatic values are from just its ordination axes values) is very difficult and point movement in the future is relative and an approximation.

Conclusions

By including several different types of metric of climate change we attempt to measure the magnitude and risk of climate change globally. Firstly, the local magnitude of climate change was measured that each gridcell will undergo in climate space during a 50 year period. While there is a very broad range of the level of change across the globe, there are very few areas that will be totally unaffected. Using multiple climate models and emission scenarios there emerged some consensus on areas that will face a high degree of climate change, notably tropical regions on the periphery of climate space and some regions of sub-Arctic space. This corresponds to regions Siberia and northern Canada. Secondly, we believe the establishment of novel climate presents a risk to local ecosystems and infrastructure and so included a measure of novelty in climate space. Those areas that will have novel climate within 50 years exist in many marginal climates in climate space, and were displayed in the Amazon, sub-Saharan Africa, South-East Asia, New Zealand and Greenland. The inverse, extinct climate, was also measured for its ability for biodiversity loss and human population risk. Extinct climate was prevalent in other marginal regions of climate, some of which coincided with novel climate space, such as Greenland, Canada, some regions of Siberia, the Andes and New Zealand. Finally the nature and direction of climate change will play an important part in determining the effects and risk on human populations and ecosystems alike. Those areas that become much more marginal, or extreme, in climate space represent those that are more likely to suffer extreme climate effects. These included many of the areas already listed in tropical climate space, such as the Amazon, central Africa and large areas of South-East Asia. Using these metrics it can be seen that many areas of climate change risk coincide with human population centres, including many cities in densely populated areas of Bangladesh, China, Malaysia and Indonesia. Other populated areas in central and sub-Saharan Africa, South America and New Zealand are also likely to become more at risk in the future. After looking at these analyses, key areas appear that will face multiple forms of climate change threat, which will present a risk to human populations.

Chapter 4: Additive threats to human populations from climate change, socioeconomics and population pressure

Abstract

Background: While climate change is a huge potential global danger, it is unlikely the most disastrous consequences will be spread evenly. Climate change itself will be heterogeneously spread and the vulnerability of human populations varies greatly across the world.
Methods: In this chapter we investigate where two forms of risk will intersect using previous constructed climate change metrics and additional socio-economic risk factors. Using a combination of climate change magnitude, regional GDP and projected population pressure we demonstrate areas that will experience both high levels of climate change and are already disadvantaged in terms of economic and socio-political stability.
Findings: Areas of highest risk (top 5% of the combined metric) are identified and compared to known humanitarian risk hotspots. Particularly prominent are South-East Asia, the Andes, the Amazon and India and Bangladesh, which demonstrate high projected population pressure, low regional GDP and high levels of climate change. These areas broadly match vulnerable hotspots highlighted in the literature.
Conclusion: Many areas that are least industrialised and likely to be most vulnerable to natural disasters and climate change are also those most likely to undergo severe climate change.

Introduction

Climate change is a global problem, but the effects are not going to be distributed evenly (Thomas *et al.*, 2008). The action of climate change on human populations are and will be affected by the resources available to a nation, the governmental infrastructure and the preparation to adapt to such changes. In such a scenario, areas that are already poverty- and water-stressed areas are going to be the most negatively impacted by climate change (Erikson & O'Brian, 2007; IPCC, 2007a; Raynor & Malone, 2001; Smit *et al.*, 1999; Thomas *et al.*, 2008; UNDP, 2006). In an unpleasant feed-back loop, political instability can be caused by increased stress from droughts, flooding and other extreme weather events, making the area in question less able to cope with future disasters leading to further instability (Schubert *et al.*, 2006). The regions that are most likely to be heavily affected by climate change are often the least equipped to deal with it. Areas that face increased poverty, population stress, drought-risk, famine-risk and political instability, or a combination of these, are often labelled as 'hotspot' areas of risk by governmental bodies and humanitarian charities (Ehrhart *et al.*, 2008; Schubert *et al.*, 2006; Warner *et al.*, 2009; Werz & Conley, 2012). This 'moral hazard' (Samson *et al.*, 2011) or 'equity gap' (Schubert *et al.*, 2006), is so-called due to the majority of causal factors of climate change being due to developed nations which will suffer relatively little, and presents a severe moral, environmental and developmental problem to the international community.

Climate change hotspots are a popular way in the literature and in governmental reports to describe those areas that face a combination of risk factors associated with climate change. These are characterised by rapid and large changes to factors that influence peoples' livelihoods at a regional and national level, and areas that are poorly equipped to cope with these large changes (Eriksen & O'Brien, 2006; IPCC, 2007b; Raynor & Malone, 2001). Factor changes that can be directly or indirectly attributed to climate change include rapid changes in ecosystem functioning, increased drought, flooding, risk of fires, cyclones or other extreme weather events (summarised in IPCC, 2007a). The underlying sociological and geographical factors that indicate how well a country will adapt to these increased pressures are also critical to understanding vulnerability, such as existing water-stress, political stability, dependence on agriculture and migration and conflict patterns (UNDP, 2011). A comprehensive report on each nation's economic, political, health and education development, is published as the UN's Human Development Index (HDI). Regions that rank low in the HDI are also likely to be vulnerable to climate change and are prime candidates for risk hotspots.

Climate change and climate space

In this chapter we consider hotspots selected by socio-economic and environmental factors and their place and shift within current and future global climate space. Climate space in this case is a form of summary of global climate variables that are relevant to the human population, such as temperature, precipitation and their annual variability, in order to reveal new information about climate change and the spatial distribution of human populations. Previously we produced a future climate 'distance' metric within climate space as a local measurement of change in climate (see Ch. 3), and we attempt to see how this will fit in amongst the other indicators commonly used to estimate risk to human societies in the future. The measure used here is that of the magnitude of climate change, which is generally agreed to be a primary risk factor in climate change ecology literature. While climate change is often included in humanitarian risk analyses along with other factors such as levels of poverty, water-stress and political instability, it is not often implemented in a quantifiable manner and most reports simply recognise that hotspot regions, for various reasons, are poorly equipped to cope with climate change. Several reports focus more explicitly on climate change as a key factor for future international planning (Ehrhart *et al*., 2008; IPCC, 2007b; Schubert *et al*., 2006; UNEP, 2011; Warner *et al*., 2009; Werz & Conley, 2012), but frequently descriptions are qualitative, include only individual climate factors, or quote mean global increases, despite the knowledge that climate change is in no way homogenous. There is an important distinction to be made between differing effects of climate change; one can measure the vulnerability to climate change or one can measure, as in this chapter, the magnitude or amount of climate change a region is likely to undergo.

Hotspots

We consider whether the magnitude of regional climate change is a usable risk metric. To do this, several commonly cited humanitarian hotspots were selected that face a combination of increased heat-, water- and famine stress from existing environmental factors and underlying socio-economic factors. Some are already recognised as climate change hotspots as well, though usually this is because these areas possess factors that will inhibit adaptation and resilience to these changes. These are, in no particular order, the Sahel; South-East Asia (covering Bangladesh and various countries in the Indonesian subcontinent); India, Pakistan and Afghanistan and the Andes and western Amazonia (see Methods for selection criteria and sources). We also include China for comparative purposes as it possesses a huge range of climate types, income types, levels of industrialisation and is considered by some (Schubert *et al.*, 2006) to be a country potentially at risk in the future. We consider the climate change magnitude each will encounter in the future and how this differs from the global average. For the socio-economic measurements HDI would have been a good indicator of risk, but data is only available at a national level, making the HDI incomparable to gridded climate change data. Instead we use gridded local population and GDP measurements, metrics that are commonly used to estimate vulnerability of an area, and compare and estimate where these factors will coincide with climate change to produce a combined risk metric. Finally, using a standardised combined metric we show a re-derivation of hotspots that face a combination of risk factors in the near future.

In this chapter the following questions are investigated:

1) What are the projected future climate shifts in the five global socio-economic hotspots?

2) What is the relationship between Growth Domestic Product (GDP) and the magnitude of future projected climate change globally and in the five socio-economic hotspots?

3) What is the relationship between projected population pressure and the magnitude of future projected climate change globally and in the five socio-economic hotspots?

4) Where are global hotspots of combined threats from high magnitudes of climate change, increased population pressure and low GDP, do these resemble the hotspots used previously?

Methods

Hotspots

Criteria for the creation of hotspots varies between reports depending on the focus of the report and the characteristics of the area in question. All hotspots selected here receive general consensus in the literature that they will face present or future humanitarian crises (Ehrhart *et* *al.,* 2008; IPCC, 2007; Schubert *et al*., 2006; UNDP, 2011). They were selected for analysis after a literature search focusing primarily on socio-economic risk factors, such as political instability, low income, poor health care and so on, but many comprehensive reports also include climate change in the list of potential threats. Hotspots were chosen from various international reports and are defined by both geographical and national boundaries, as accuracy demanded. First and foremost in most socio-economic hotspot analyses is the Sahel, the semi-arid grassland along the border of the Sahara and the home to roughly 160 million people, most of whom are directly dependent on local agriculture. In the last century it has already been prone to large periods of drought and famine (UNEP, 2011). It is also the expression of a large and unpredictable migration zone from sub-Saharan Africa towards Europe, leading to population and resource stress in multiple areas at once (UNEP, 2011). It is also home to some of the world's poorest and least developed nations (UNDP, 2011), which suffer frequent periods of civil unrest and political instability. As such, because of the combination of these factors, it is often quoted as one of the world's most at risk regions and has been the focus or partial focus of several international reports (Ehrhart *et al*., 2008; Schubert *et al*., 2006; Warner *et al*., 2009; Werz & Conley, 2012; UNEP, 2011) and even small predicted levels of increased temperature and water-stress threaten to send the region into a long-term humanitarian crisis (UNEP, 2011). South-East Asia, especially Bangladesh, is also frequently discussed as a future risk hotspot for its vulnerability to flooding from rising sea-levels, precipitation changes resulting in more unpredictable harvests and more flooding, and growing population pressures (IPCC, 2007b; Warner *et al*., 2009). Drought and war-stricken Pakistan, Afghanistan and North-West India form another band in central Asia with rapidly rising population centres (Schubert *et al*., 2006). Finally the Andes is also commonly included, concerning both its both high and low altitude regions due to the fragility and importance of its high biodiversity ecosystems and the encroach of rapid glacial melt and deforestation (Schubert *et al*., 2006). All these regions share some characteristics, each with its own background and history, and are already among the most vulnerable regions in the world. The ability to adapt to climate change in these areas is severely compromised and thus any predicted changes in these areas are of importance to international planning.

The boundaries of each hotspot were selected as follows (Table 4.1). The Sahel was not selected along its entirety, but along the western range of its extent in the nations of Mauritania, Senegal, Niger, Nigeria, Mali and Burkina Faso due to the frequent drought risk, expanding desertification, sporadic political instability and areas of extreme poverty. South-East Asia was defined as Bangladesh, the surrounding regions of India, Myanmar, Cambodia, Vietnam, Laos and Indonesia due to the risks of ecosystem degradation, flooding, poverty and large projected population increases. Central Asia was defined as Iran, Afghanistan, Pakistan and the north-west region of India, already arid areas that have suffered in recent years from instability and conflict. The Andes were defined as the national boundaries of Chile, Peru, Ecuador and

Colombia, covering both mountainous and upland rainforest and selected because of their vulnerability to glacial melt, ecosystem changes and areas of extreme poverty. Finally, China is included for comparative purposes and the large potential of ranges of climate changes and population and GDP increases. See Figure 4.1 & Table 4.1 for summary of selected hotspot zones.

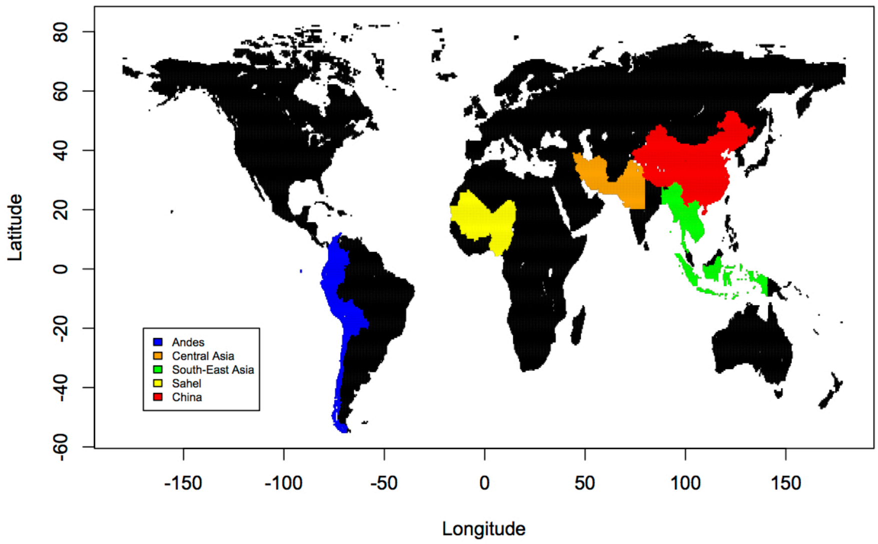


Figure 4.1: Map of highlighted human risk hotspots chosen for investigation (see Table 4.1).

Table 4.1: Key statistics for each hotspot including the key risks each faces. Information was taken directly from the data sources used in methods, correct for the year 2000 (Hijmans *et al.*, 2005; van Vuuren *et al.*, 2006). Key risks and criteria for hotspots selection are included for the Andes (Malcolm *et al.*, 2006; Schubert *et al.*, 2006), Central Asia (Schubert *et al.*, 2006), South-East Asia (IPCC, 2007b; Warner *et al.*, 2009), the Sahel (Ehrhart *et al.*, 2008; Schubert *et al.*, 2006; Warner *et al.*, 2009; Werz & Conley, 2012; UNEP, 2011) and China (Schubert *et al.*, 2006).

	Andes	**Central Asia**	**South-East Asia**	**Sahel**	**China**
Area (sq. km)	6,448,940	6,468,960	6,560,483	5,439,550	9,586,983
Total Population	96.6 million	523.1 million	513.7 million	156.5 million	1.26 billion
Average Population Density (per sq. km)	30	150	146	35	137
Average GDP (per sq. km)	0.16	0.24	0.32	0.03	0.32
Main Biome	Mountain, sub-tropical rainforest	Desert, semi-arid grassland	Rainforest, Coastal	Desert, arid to semi-arid grassland	Varied
Key Risks	Flooding, drought, biodiversity loss	Poverty, political instability, drought	Flooding, population pressure, poverty	Poverty, drought, conflict, political instability, desertification	Natural disasters, poverty, precipitation changes.

Data

Climate change data are taken from 19 climate variables from WorldClim (for 2000 data) (Hijmans *et al*., 2005) and CIESIN (for 2050 data) (Ramirez & Jarvis, 2008). The standard model and emission scenario is HadCM3 A1b using the present and 2050 time-slices. The metric of climate change 'distance' is calculated as the euclidean distance of each grid point from its corresponding future point in climate space. This calculates the similarity in climate in the future to the present considering all climate factors at once. The distance metric is used throughout as a measure of magnitude of climate change in logged form, the larger the figure the more climate change a grid cell is estimated to undergo in the next 50 years (see Chapters 2 & 3 for more details on climate space and climate change metrics). Multiple climate factors were included in the constructed climate space as while temperature and precipitation measures are useful and are usually taken as indicators of general climate trends and climate change velocity (Ackerly *et al*., 2010; Loarie *et al.,* 2009; Saxon *et al*., 2005; Williams *et al*., 2007), there are multiple other biologically important climate variables which can inform about the habitability and potential increased risk in an area. Particularly variation of both temperature and precipitation throughout the year, and the extent of the extremes of both are important at predicting stress and risk on a population (Case *et al.*, 2007; IPCC, 2007b; Naylor *et al.*, 2007; Sherwood & Huber, 2010; Small & Cohen, 2004). Climate space analysis allows all these factors to be included at once and weighted against their effect size, and the total distance moved by a point is indicative of changes in multiple factors. These are purely climatic measurements, but previous research suggests they are strongly collinear to other more direct measures of human importance, such as plant growing seasons and agricultural capacity (Samson *et al*., 2011; Stephenson, 1998).

Population and GDP data were taken from Netherlands Environmental Assessment Agency (van Vuuren *et al*., 2006) due to the wide range of available emission scenarios, climate models and future times slices and was gridded on 0.5º cells and aligned with latitude and longitude of the climate dataset to be directly comparable to the climate change data used in previous chapters.

Risk Metrics

The projected increase or decrease in GDP per grid cell was calculated as the difference between the GDP of a grid cell in 2000 versus its equivalent in 2050 taken from estimated projections of van Vuuren *et al*., (2006). Population density change was calculated in the same way; as the difference between population density in the present and future time-slice (van Vuuren *et al*., 2006). Comparisons were made between pairs of risk factors; climate change magnitude, GDP, Population Density, GDP change and population density changes to compare these metrics globally and within the selected hotspot regions.

The combined risk metric was created by standardising climate change, population size and regional GDP on a 0-1 scale and summed. Regional GDP was inverted so lower GDP creates a higher risk metric. This was compared globally and in selected hotspots.

Finally a re-derivation of hotspots was included by using the highest 5% combined risk grid cells to create a new map of highest risk areas. This was compared to the hotspots selected from the literature.

Results

Climate Change in Hotspots

Using the defined hotspots we investigate whether these regions will undergo greater climate change than the global average. An initial logged box plot of each region shows significant differences between each hotspot compared to the global average (two-tailed T-Test all $P<0.01$) (Fig. 4.2a). These are relatively small differences, detectable in a large dataset, but it seems central Asia and China will change at near or just under global averages, and South-East Asia and the Andes will change much more rapidly. There is a range of responses as the hotspot regions often cover multiple biomes and geographical boundaries. The Andes in particular show the potential to have extremely large changes to climate, right up to the maximum amount seen in the global data, corresponding to high-altitude glacial melt and ecosystem shifts.

GDP and GDP Change in Hotspots

Gross domestic product on a regional level measures market trading price in US dollars for per capita income and forms a primary measure for various human welfare statistics. The GDP of each hotspot region on a 0.5º resolution was compared to the global average and then visualised using metrics of climate change and GDP (Fig. 4.2a), within which data ranges in the hotspots were compared to the global data (Fig. 4.2c). In both, the Sahel and sections of the Andes show some extremely low-income areas, but for the most part GDP is at or just above the global mean (two-tailed T-Test all $P<0.01$) and climate change is greatest in these defined hotspots in the Andes and South-East Asia. Hotspots, as defined here, do not seem to have consistently lower GDP than global means, but this does not mean some regions within these hotspots do not still have extremely low income.

GDP change shows the increase or decrease in income within an area between 2000 and 2050. All hotspots show increases above or near the global average (Fig. 4.2b), though note the Sahel has some areas that will develop much less than the global average, with very little economic development.

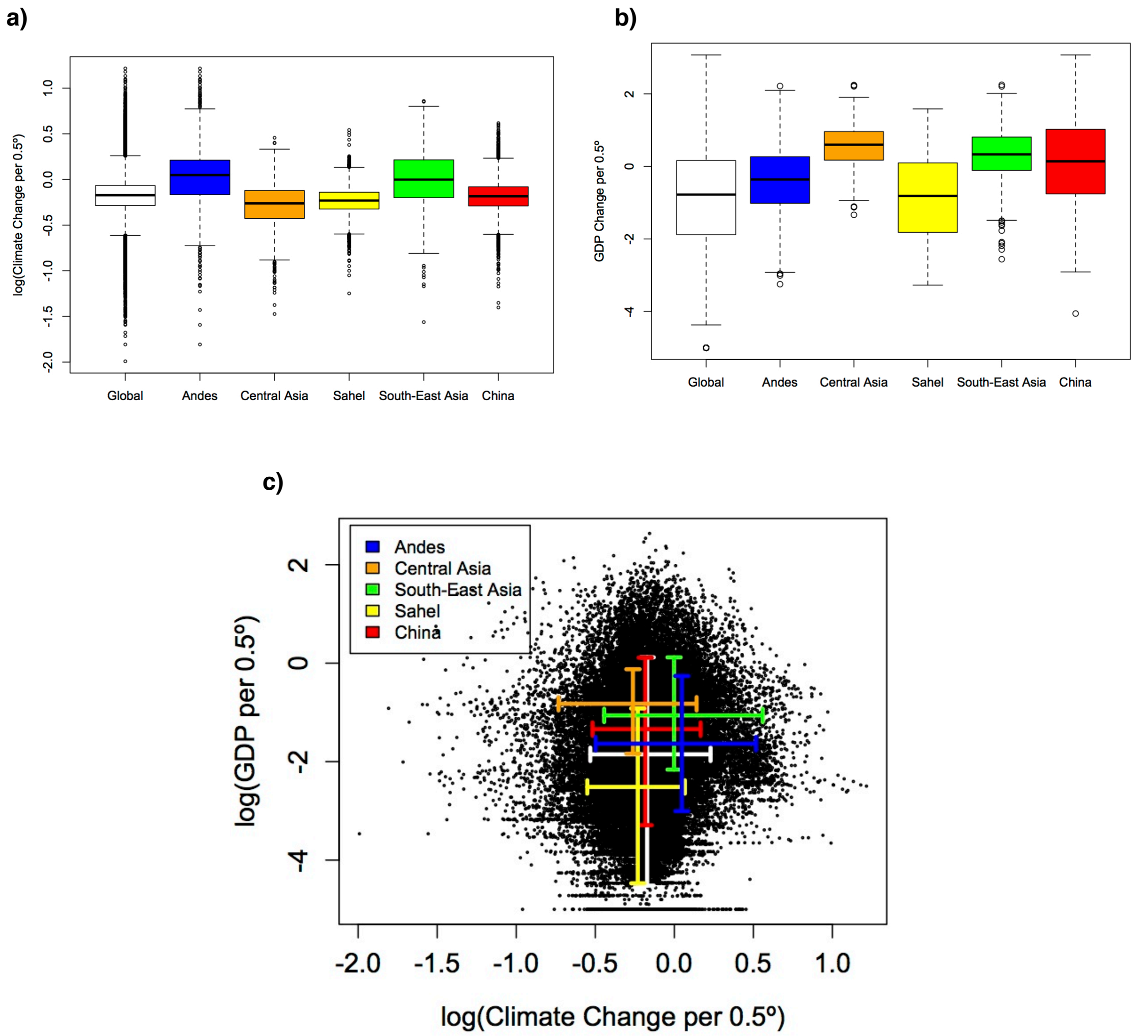


Figure 4.2: a) The level of climate change (logged) faced globally and in each selected hotspot region. b) GDP growth of the world (logged) and in each selected hotspot region between 2000 and 2050. c) Climate change and GDP of each grid cell across the world (both logged). Over this are shown the 95 percentile range of global data (in white) and each hotspot (see legend).

Population Size and Population Growth in Hotspots

Population size in hotspots all emerged as significantly above that of global average (two-tailed T-Test all $P<0.01$), and more relevantly all, bar the Andes, have extremely high population centres (Fig. 4.3a). South-East and Central Asia in particular possess population centres that fall even higher than the 95% global distribution of population (Fig. 4.3c). It seems hotspots do commonly have higher than average population sizes, but this is less relevant to vulnerability than the fact that they all possess some areas of extremely high population density.

Population growth takes the expected population for each grid cell, adding to population burdens of an area. All hotspots, apart from the Andes and China, show significantly higher than average increases in population by 2050 (two-tailed T-Test all $P<0.01$) indicating greatly increased population stress (Fig. 4.3c).

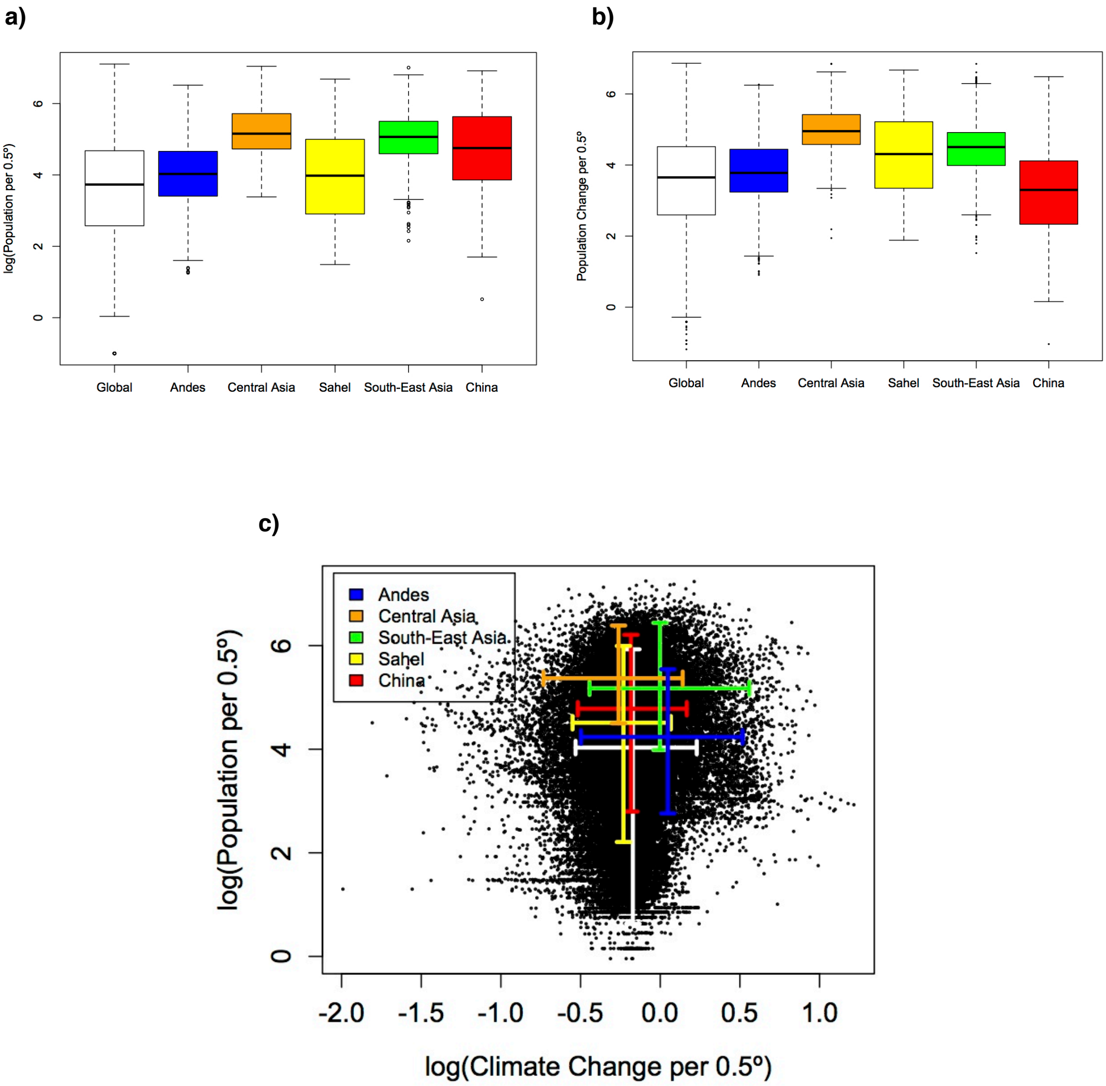


Figure 4.3: a) Global population in 2050 compared against the population size for each of the hotspot regions. b) Global population growth between 2000 and 2050 compared against regional population growth for each selected hotspot. c) The degree of climate change and the population density of each grid cell across the world (both logged). Over this are shown the 95 percentile range of global data (in white) and each hotspot (see legend).

Thresholds and a Combined Risk Metric

Considering all metrics separately has advantages, but combining makes it easier to judge the risk of an area altogether. Figure 4.4 shows a comparison of global risk against each regional hotspot. All are shown to be at significantly higher risk than the global average (two-tailed T-Test all $P<0.01$), with the exception of the Sahel ($P=0.06$) which proves to be almost identical to global trends.

This global combined risk metric can be plotted to show where the highest areas of risk are and thus re-derive hotspots to compare them to the ones used previously selected from the literature (Fig. 4.5). The areas of highest risk are largely approximate to the ones used previously (Fig. 4.5), though with minor, but potentially important, variances. The southern Andes appear as very high risk, though areas further north in Chile show less, and the northern Andes and surrounding forested regions on the western coast also show high levels of risk especially around the northern Amazon. South-East Asia also comes out as consistently high risk, from across the Indonesian islands and Vietnam to Bangladesh and surrounding India. However, in this method of analysis this area of risk also extends into Nepal and similar Himalayan regions across which risk appears to be high. Central Asia displays less risk than its hotspot status would expect, and while India and Pakistan do show regions of high risk central Asia maybe would not be classed as an obvious hotspot. Surprisingly, the Sahel does not show up strongly in this analysis though there is some indication of a band of risk in western Sahel and further south in central and sub-Saharan Africa. There is no real indication of very high risk across the region. China, as expected, shows a wide variations in magnitude of risk and climate change. Western and central China appear as low risk, but eastern China, especially coastal areas, appear as very high risk due to much higher population centres. Other areas that reveal consistent high risk not discussed so far include across Central America, portions of the Rockies in western North America and further portions of Oceania mostly consisting of more islands in and around Papua New Guinea. By defining a 'threshold' of risk we can re-derive hotspots with more clearly defined boundaries.

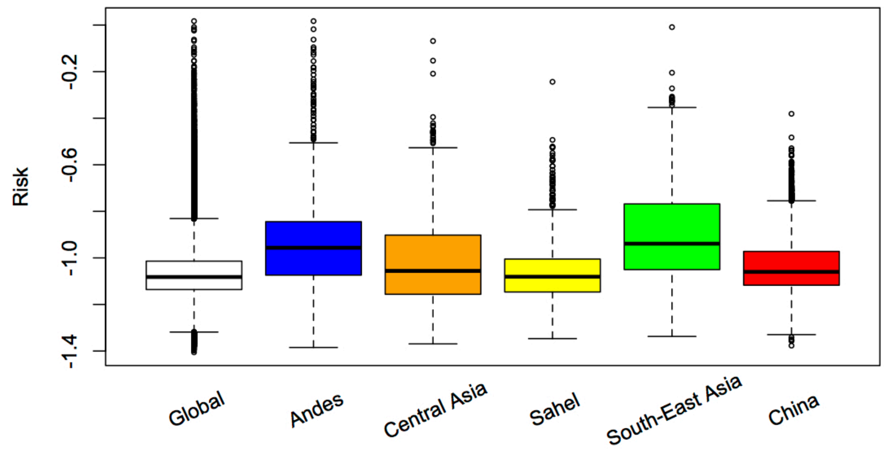


Figure 4.4: An additive combined metric of all three risk factors (climate change, GDP, population) of the world and that of each of the hotspots. (Risk metric is logged as compared to Fig. 4.5).

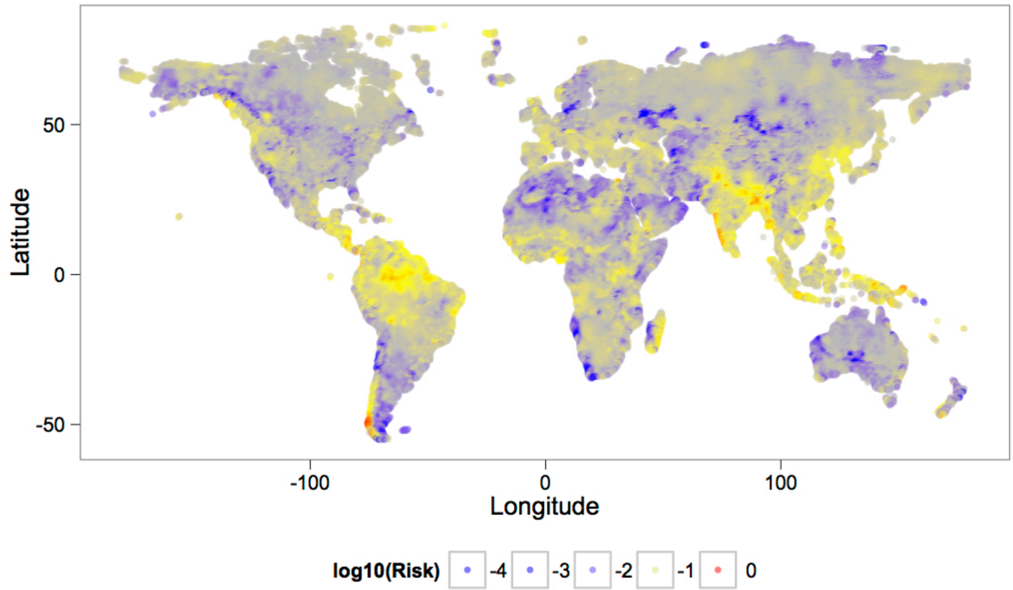


Figure 4.5: Additive combined risk across the world (climate change, GDP, population).

The threshold chosen is somewhat arbitrary, but represents the top 5% of risk as defined by the combined metric. This shows hotspots similar to those we stated before, but with slightly different distributions than the ones we used as informed by the literature (Fig. 4.6). The north Amazon and eastern brazilian coast shows wide-spread large vulnerability to climate change, as well as the the Andes and western coast. Central America and portions of the Rockies also appear above threshold values.

Highest risk areas in Africa appear more in sub-Saharan Africa as well as the Sahel, with scattered portions further south in central Africa as well. Madagascar appears prominently as a risk zone.

Conclusions about South-East Asia prove broadly correct with high risk throughout with a greater spread in Himalayan regions as well as most coastal regions. Central Asia does not appear prominently, but instead southern India appears as a high-risk zone. Coastal China also appears strongly. At lower thresholds, more of sub-Saharan Africa is included in the risk zone, as well as more of South-East Asia and the Rockies, and in addition the Mediterranean appears as a risk zone.

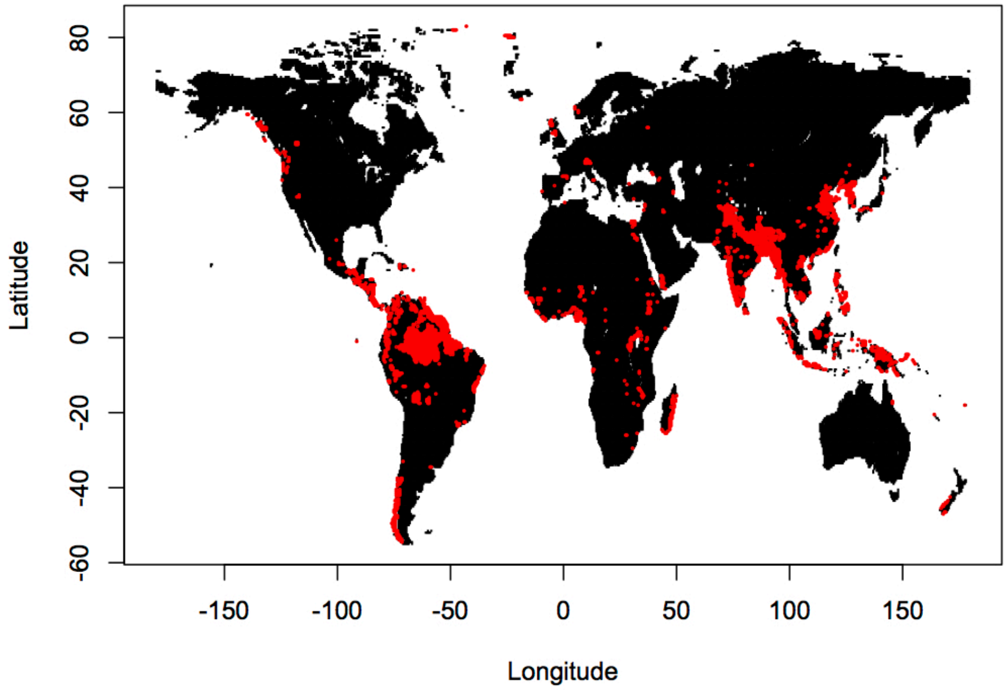


Figure 4.6: Top 5% areas of risk highlighted in red as determined by combined risk metric.

Discussion

Hotspots are a key way to highlight risk to some of the most vulnerable people on the planet. In this chapter we attempted to use magnitude of climate change as a possible metric of risk, alongside other key indicators commonly used in international development literature such as regional income, water availability, population pressures and governmental support. Magnitude of climate change has not been frequently used in this way, often superseded by estimates of 'tipping-points' and global means, but it forms an easily quantifiable metric to measure risk. Even without heterogenous climate change countries with lower income and other sociological disadvantages would be at more risk, but the results discussed here show that it is these countries precisely that will undergo the largest amount of climate change, further adding to the existing burden of these undeveloped countries. With the addition of some simple economic and population variables these patterns become even starker. Identified as the most at risk areas include South-East Asia, from Indonesia to mainland Vietnam and other coastal countries, Bangladesh and large portion of India and coastal regions of China. The Himalayas also appear as a high vulnerability area. South America throughout the Andes and Northern Amazon also forms a hotspot, which could possibly be divided into two, that appears strongly as at risk. Surprisingly the Sahel, the focus of numerous reports appears to be a less strong hotspot, though why this is is unclear. Our results broadly match the informed socio-economics hotspots listed in many reports, but differ strongly in some ways and the use of the top 5% threshold shows more clearly the at-risk zones in our analysis. Hotspots are a key way to inform climate change politics and magnitude of climate change proves to be a useful metric to add to the suite of risk metrics already available.

Climate Change Risk Factors

The climate change distance metric used here comes from an ordination condensation of 19 bioclimatic variables that cover most factors that are important to ecosystems (and by extension) human spread. By turning these into climate space axes, more information can be gathered and used simultaneously for analysis. By comparing the relative positions in climate space of a point in 2000 and its projected position in 2050, a quantified measure of climate change can be produced. The direction in which this point moves also informs on the nature of the change, whether it be temperature increases or shifts in precipitation patterns. Rapid climate change can be considered a useful metric for risk as more rapid change equates to less time for adaptation measures, more unpredictable changes, and more chance of existing infrastructure being overwhelmed by possible extreme events such as fires, droughts, heat-waves and other extreme weather events. More commonly, the concept of thresholds to biome change and human risk are considered such as increased frequency of droughts and so on (Warner *et al*., 2009; Williams *et al*., 2007), but these extreme events are less easy to quantify reliably so we would make an argument that magnitude of climate change is a useful metric to add to this. Previous research has considered rapidity of climate change but more frequently in the context of conservation (e.g. Ackerly *et al*., 2010; McCarty, 2002; Pearson *et al.,* 2003; Thomas *et al*., 2004) and ecosystem shifts (e.g. Alley *et al.,* 2003; Hobbs *et al*., 2006; Hughes *et al.,* 2003; Loarie *et al*., 2009).

As mentioned, this means that climate change as a metric does not include some climate related factors such as increased frequency of extreme weather events which may be a major future problem in vulnerable areas (Ehrhart *et al*., 2008). As the IPCC4 report (2007a) points out there is “no single metric for climate impacts [that] can provide a commonly accepted basis for policy”. As such the regional background to an area is key to how a population can respond to increased pressure from climate change, from economic and demographic factors to the level of centralised government, international aid and health and education levels. This is summarised at a national level by the UN as a human development index. For this analysis we select gridded population and GDP as it forms a comparable dataset to the distance metric produced previously at 0.5^{o} and projections are available for both at relevant time slices. Population size is an obvious measure of how many people are at risk within an area, but also informs partially how stressed a landscape is. Heavily populated areas, such as cities, may have larger investment in infrastructure but in many poorer cities, such as in South-East Asia this over-crowding leaves less room for migration and adaptation. By using the difference between grid cell populations between 2000 and 2050 we also gain a rough idea of population growth. High population growth indicates higher usage of resources, more people potentially at risk from natural disaster and famine and is sometimes linked to greater migration patterns (Huppert & Sparks, 2006; McNicoll, 1984; Preston, 1975). A pattern in developing countries with expanding populations, especially those that face environmental pressure, is a large tendency for migration towards cities, which is a particular cause for concern as rapidly growing population centres can cause cities to grow above normal limits and often do so with little regard for potential future risk (McGranahan, 2007). Gridded GDP measures local market trading value of an area, and is a basic indicator of local wealth, which is often spread very heterogeneously throughout a country making gridded GDP a more detailed indicator than on a national level (van Vuuren *et al.*, 2007). Poverty-stricken areas indicate less available reserves and resources to recover and adapt to adverse conditions and therefore low GDP is an indirect indicator of the risk an area will face from other factors, such as climate change. Between these three factors a reasonable measure is produced that takes into account several key indicators of risk from climate change.

Selected Hotspots

Before commencing the hotspot analysis key regions were selected based upon previous literature: the Sahel, South-East Asia, Central Asia, the Andes (Table 4.1; Fig. 4.1). China was also included for comparison as it is a large country with a wide variety of biomes and potential responses to climate change. These regions are characterised by low incomes, localised populations pressures, existing natural disasters and political instability. It is generally agreed that all these factors make a country less adaptable and resilient to the likely effects of climate change, whether that be increased flooding, drought or rapid ecosystem changes.

The relevant metrics were compared and the initial results compare favourably to expectations. The selected hotspots generally exhibit higher levels of climate change (Fig. 4.2), high levels of population density and growth (Fig. 4.3) and some mixed results of GDP (Fig. 4.2) compared to the global average. GDP in the Sahel particularly is low compared to the mean and spread of the global average (Fig. 4.2b) Comparing each measure independently has limitations however, as hotspots frequently appeared as having both higher GDP and population at the same time. Considering the metrics in isolation is not necessarily helpful and it is the coincidence of multiple risk factors that are more important. Differences appear small in some cases as the very large datasets in question cover a large range even within the hotspots. Climate change distance, however, did appear as significantly higher than the global average and it appears clear that some of the hotspots in question will in at least some of their ranges undergo rapid climate change (Fig. 4.2).

Combining Risk Factors

By combining the metrics into a single risk factor it becomes easier to look for the coincidence of risk factors within an area. All hotspots appeared as significantly higher in risk than the global average, apart from the Sahel (Fig. 4.4). This can also be mapped on a linear colour scale and, with some discrepancies in extent and borders, all hotspot regions appear strongly at risk, though central Asia perhaps less than expected, with the exception of the Sahel (Fig. 4.5). Finally, by using a threshold limit, in which only the top 5% at risk gridcells are selected, these hotspot regions can be defined more clearly (Fig. 4.6) and compared to the position of the hotspots chosen initially using socio-economic factors. South-East Asia appears very heavily at risk, perhaps even to a greater extent than our initial selection of regions expected. Increasing temperature, unpredictable rainfall and large increases in population mean the whole region appears as high risk. Bangladesh especially appears as one of the highest risk areas in the world, as covered in many other reports (Ahmed *et al.,* 1999; Ayers & Huq, 2008; Brouwer *et al.,* 2007; Werz & Conley, 2012). After this, large sections of South America also appear at risk, especially regions of the southern Andes which will undergo extremely rapid levels of climate change and glacial melt at high altitudes. The northern Amazon is also an area for concern as both upland and lowland forests appear at risk from large scale precipitation changes leading to the risk of ecosystem collapse (Mahli *et al*., 2009) though this is not specifically modelled in this estimation. The coast of Brazil is also at risk due to its large population centres and high levels of climate change. Central Asia does not appear as strongly as its hotspot status would expect, though large areas of India appear strongly at risk, primarily from decreased rainfall and higher maximum temperatures. A reasonable guess for why this is true, is that most reports include this region as a hotspot due to its increasing instability and potential for conflict, factors which are not included in this analysis of risk. This does not mean the region is not of high concern, but demonstrates the need in some cases for a full consideration of all factors at play within a region. On the other hand, upland India and the Himalayas as a whole appear very strongly at risk, as many other mountainous regions do, due to the potential for rapid glacial melt and natural disasters. Finally, and most surprisingly, the Sahel does not appear strongly at risk in terms of either climate change or the combined risk metric. Figure 4.5 does seem to imply a band of higher risk across the sub-Saharan and the Sahel, but considering the Sahel is agreed to be one of the most vulnerable regions in the world this is still surprisingly low (Ehrhart *et al*., 2008; Schubert *et al*., 2006; Warner *et al*., 2009; Werz & Conley, 2012; UNEP, 2011). By lowering the threshold of hotspot to 10% this region does appear, but again this makes it only a medium-risk region.

It is generally agreed that the Sahel will be a key humanitarian hotspot in the future, so why does it not appear strongly in this analysis? One possible idea is the concept of thresholds as the increasing desertification of the Sahel, increasing population and decreasing food production due to drought threatens to reach a crisis point (UNEP, 2011). Such a tipping-point is not specifically measured in this analysis. Another is that other sociological factors that are key to the vulnerability of an area are not included, in the Sahel the belt of migration and political instability are key factors for concern as well as the increasing frequency of droughts and unpredictable rainfall (Held *et al*., 2005; UNEP, 2011). This reveals one weakness in this metric, that rare extreme events are difficult to model and therefore we cannot predict frequency. It is expected that extreme climate events will increase in frequency in some areas (Lerner-Lam *et al*., 2005; Rosenzweig, 2001; Van Aalst, 2006), but our climate variables measure averages over many years and therefore do not predict one-off events. Other reports focus on this (Ehrhart *et al*., 2008) and in this case it highlights the need for other metrics to fully understand the challenge presented by climate change as extreme weather events increase in number. The same applies to central Asia, as mentioned previously the reasons it is commonly selected as a socio-economic risk hotspot are less to do with income and population and more to do with natural disasters and political instability, factors that are not included in this analysis.

The combined metric uses rough relative measures and assumes relatively consistent factors with little inter-annual variation, so it measures average climate change risk. In conclusion, a better metric of risk would include more factors of relevance to risk. While adding sociological factors can make a metric more relevant, it is also worth remembering that the more factors are added to such an analysis the more difficult any results are to interpret as signal can be lost amongst data 'noise'. One final point to consider is that in this case all predictions were based on one climate model for one emission scenario (HadCM3 A1B). In this case, A1B is a midline scenario and other models may show much worse risk in some areas and a difference in some risk extent, in which case the Sahel may indeed appear as an area of strong risk. Similarly, using an average of climate models may change the extent and spread of hotspots. HadCM3 predicts slightly different and more severe changes in precipitation levels in the Amazon than other models due to potential inaccuracies in the original present-day data (Huntingford *et al*., 2001; Li *et al*., 2006), and when considering other climate models the Amazon may appear less strongly as a hotspot. Such an inclusion would require more time, which is why it was not included here, but would increase the security of conclusions.

Conclusions

From this analysis, including climate change distance shows that the most vulnerable regions in the world; those that are poorest, most unstable and the focus of various international aid reports, are also going to suffer some of the most drastic changes in climate. Socio-economic hotspot regions selected from the literature resemble the hotspots created by our climate change metric and combined metric to a reasonably close degree, although some key differences do exist. Using a combination of climate change, regional GDP and projected population size we conclude South-East Asia, the Andes, the Amazon and India and Bangladesh are particular risk hotspots. We do not find extremely high levels of risk in the Sahel as predicted, but there are several potential reasons for this. These conclusions demonstrate something of the disparity of how those most vulnerable to climate change, those poorest, unstable, and least industrialised, are also going to suffer the most, and highlight the challenge to international development in the future.

Chapter 5: General Discussion

Climate is one of the main drivers of the geographic distribution of life on Earth. This thesis investigates the current distribution of human populations in relation to current and future climate conditions. Here, I discuss the main findings of my thesis in the context of three important aspects of research on climate change impacts on humans: 1) the methodology of quantifying climate change impacts; 2) treating humans as a 'species' in bioclimate envelope modelling; 3) combining climatic and non-climatic factors to assess threats to human societies from future climate change. Using these methods of analysis we isolate those regions that are most at risk from climate change, and human populations that face the highest levels of threat from climate change.

Quantifying climate change impacts

Climate science is complex, and understanding the climate in all of its permutations of input and effects of geological cycles, oceanic systems and currents, solar radiation, weather patterns and ever changing effects of biomes and ecosystems across the world is a huge undertaking. The problem of understanding this system has become more pressing as it is expected that due to anthropogenic carbon output from energy generation, industry and similar, the climate is undergoing rapid changes and the atmosphere, as a whole, has been increasing in average temperature by nearly 1ºC in the last century, and is likely to increase within the next century by several more (IPCC, 2007b; Stern, 2006). The multitude of consequences that stem from a heating of the Earth's surface and atmosphere due to greater heat retention include the melting of the polar icecaps, an expected sea-level rise, and changes in global weather systems leading to changed temperature and precipitation cycles. These changes threaten to severely affect human and ecological systems alike around the world. Understanding how the climate will change is dependent on many different factors; some independent of our actions and some very much dependent, including future increases in carbon emissions and our responses to climate change. There now exist multiple predictive models of climate as it will change in the next century, and these have been used to investigate the direct and indirect consequences of climate change on individual species, ecosystems and on humans themselves (Cramer *et al*., 2001; Johns *et al*., 2003; Patz *et al.,* 2005; Roeckner *et al*., 2003; Yukimoto *et al*., 2001). Pressing threats include those of increased frequency of extreme weather events, droughts, flooding, spread of disease and ecosystem collapse, all of which will require large efforts to counter and overcome, and as such the need for predictive analysis to characterise and understand human risk and responses to climate is important to international planning.

Having said that climate change will affect human societies, it is not always obvious how exactly this change will be effected and which factors are most critical to human populations; the exact nature of risk varies depending on where in the world is being investigated. As such, regional climate models and risk analyses are critical for policy decision making and provide important additional details on linking climate change and the actual impacts on humans and other ecological systems (Black *et al.*, 2011; IPCC, 2007a). Using observed weather records to model Earth's climate and its responses to global warming, changes in gridded temperature and precipitation variables can also offer information on the nature and magnitude of change on a local level. In this study, a combination of ecologically important climate factors and niche modelling techniques were included to investigate the variable links between climate and human distribution across the Earth's terrestrial landmass, the relative extent and distribution of climate change and how the climate will change across the world, and how this abstract information of climate change can be related to risk analysis on human societies. We attempt to add to the methodology and information available to explain climate change and risk.

Niches

A niche constitutes the parameters that an organism can successfully live, breed and persist in. Typically the nearer to the boundaries of this theoretical niche an organism is the less it is suited to survival. The factors that make up a niche are both biotic and abiotic, and include climate factors such as temperature, precipitation, seasonality and average daily range, as well as the more local effects of terrain and altitude variables. In addition the niche of an individual species is also determined by the type of biome that exists and the species that an organism will interact within its environment. These factors have obvious links and feedback mechanisms between them, and as such the extent to which any one factor is relevant to estimating distribution of a species over another is nearly impossible, as factors act together and simultaneously (Chuine, 2010; Johnstone & Chaplin, 2003; Parmesan *et al*., 1999). Within this general description there are several variations of concept that can be employed. The original concept of the niche simply describes the possible locations a species can survive (Grinnell, 1917), or alternatively areas a species perform a certain 'function' (Elton, 1927). More recently, and more relevantly to the methodology used here, the Hutchinson niche (Hutchinson, 1957) describes a "hypervolume" or multidimensional space composed of all the factors and parameters in which a species functions. These bioclimate envelope models, or niche-based models, or habitat models as they are variously called, all rely on estimating and predicting the distribution and spread of species over space and occasionally time. Examples, both successful and unsuccessful, of modelled distributions using this approach abound in the literature from the earliest attempts (e.g. Kuenzler, 1958; Southern, 1938; Wallace, 1958) to modern iterative models (e.g. Buse *et al*., 2007; Hu *et al*., 2003; Mason *et al*., 2008; Yu & Suganthan, 2010).

Climate Space

The analysis of climate in this study used the concept of climate space as its methodological framework. The climate of a region is the multivariate climatic conditions of that region. A region can be a geographically defined area (e.g. an island), a species range, or, as in this case, areas with different human population densities. Climate space is a concept developed as a logical continuation from the previously mentioned niche *n*-dimensional space (Hutchinson, 1957). It is a quantifiable method of comparing multiple climate factors, in this case by using ordination analysis as a method of comparing climate factors that do not follow the same scale or power. A constructed climate space can compare the importance and effect of temperature, precipitation and seasonality variables on human population distribution.

Constructing a climate space

In this study, we found that humans occupy the entire global climate space (Fig. 2.1). From first principles, we hypothesized that humans would mostly occupy the centre of global climate space, however this was not the case. High population densities are frequently found on the hot margins of the climate space (Fig. 2.4). In the colder and drier regions, such as Canada and Siberia and general tundra, human population density was very low, and indeed as climate moved towards more temperate values population increased, or more accurately the proportion of higher density population categories grew greater, and at the other end higher temperature and low precipitation areas (i.e. deserts) did show mildly decreased population densities (Fig. 2.1; 2.3; 2.4). However, at the other corner of climate space, areas with high temperature and high precipitation (i.e. the tropics) had extremely high population densities that were present right up until the very edge of available climate space (Fig. 2.1; 2.3; 2.4). This particularly represents areas such as south-east Asia, central America and parts of Africa (Fig. 3.4). Whether this is due to a disequilibrium of humans and climate or whether humans really do thrive in high temperature and high precipitation areas is unknown, but it may well be a mix of both. This does not necessarily translate into risk simply because they are at the edge of climate space, but any change that does occur is more likely to tip these areas into novel space, and as such responses here are particularly unpredictable.

Non-climate drivers of human population densities

There is no question that humans are influenced by many factors that are non-climatic, though climate still plays a large role in human growth, spread and density through physiological, energetic and agricultural limits (Samson *et al*., 2009). Human ecology is often thought of separately to animal ecology. While it is recognised that climate has driven human distribution in the past, the sociological stance often bases human distribution on wealth, availability of resources and other human-specific drivers of distribution. At a local scale, in a similar way to many mammals, human settlements are limited by resource availability, especially water and good growing conditions. While these both are linked to climate, other factors begin to become involved in a human population.

In sociology literature, climate is included as an important factor in population trends in pre-industrial societies, but it is often assumed that climate and human population distribution are not strongly linked. On a greater scale this is incorrect even today, as areas such as Siberia, the Sahara and Antarctica, at the extremes of Earth's climate, are less hospitable to and populated by humans than other more temperate areas as is shown in our analysis (Fig. 2.1; 1.4). At a regional scale sociological factors become more important and, as demonstrated in Chapter 2, there is much to describe in human spread that is not explained by climate factors. It is true that urban societies appear to grow with little attention to climatic conditions, and the niche humans inhabit is one mostly constructed by themselves. The highest population density category used in Chapter 2 (1000+ people per square kilometre) are urban environments and are present throughout climate space with a very large spread (Fig. 2.1; 2.4). A human cultural niche is influenced by the education system, the level of industry, the health system and wealth available to the population, and all of these sociological factors have links to population growth and distribution (Holdren *et al.,* 1974; Zhang *et al*., 2007).

Depending on the region of the world in question and its history, the dependence of human populations on climate is very variable. The larger the amount of resources available, typically equivalent to wealth in a developed nation, the more detached a population becomes from climate factors, and so increases its resilience to changes in the environment as compensatory measures become possible (IPCC, 2007b; Lee, 1987). For example, in developed nations dependence on local agricultural workforce is often as low as 1-2%, but in the poorest regions of the world dependence on local agriculture is as high as 85% (UNDP, 2002). Such dependence on the success of local harvests means a greater risk from crop failures or climate change (Barnett *et al*., 2007)

Stable population growth is commonly linked to resource availability and medium levels of wealth (Lee, 1987), and the reduction of infant mortality rates usually by the construction of a health-care system (Cohen, 2003). Humans are also a particularly mobile species, with great movement present after periods of disruption and a common trend of migration towards cities (Black, 2008). While all of these factors can be influenced by climate, the human cultural niche overcomes and expands many of the limitations set by physiology and climate. As such, a purely climatic approach will never explain the whole of human distribution or present a cohesive estimate of the effects of climate change on human societies. Although it is undeniable that all these factors do have a large effect on human distribution, it is also true that climate change threatens to put large areas of the population at risk, for multiple reasons (IPCC, 2007b).

Humans as species in bioclimate envelope models

A key assumption throughout this thesis stems from the application of bioclimate envelope modelling to explain human distribution and future risk. While this methodology is well established in ecological literature and correlations of distribution to climate are used to estimate species' reactions to climate change, how does this methodology compare when using humans as a test species? After the construction of a human climate space in Chapter 2, we investigated this question by applying similar techniques to humans.

Animal Ecological Niches

While niche modelling can be applied to any organism, differences in approach occur depending on the life-history of the species in question. For example, when examining plant niche models the effective growing season described by temperature, precipitation patterns and sunlight exposure can be used to predict distribution over a large area (Nix, 1978; Rehfeldt *et al*., 2006). Biotic factors can be invoked to explain propagation and spread patterns. In animal ecology, species niches can be constructed using similar physiological data to calculate limits to distribution, though correlative methods are more common (Pearson & Dawson, 2003). Many of the climatic factors that affect distribution are the same in animal ecology, especially temperature and precipitation variables, but other important distribution factors are indirect through food and nutrient availability (Gregory & Gaston, 2000; Smith, 1982; Vivas & Saether, 1987). Not every factor affecting distribution can be included and the more complex the system involved the less capable we are of modelling it accurately. Factors such as social patterns, breeding seasons, survival trends and occasional extreme events are often hard to quantify and include, but despite this animal niche models are an important and effective way to build understanding of organism distribution, and future conservation and risk planning.

When predicting future changes in distribution from niche models the output necessarily becomes less reliable when extrapolating outside of the conditions and data that were used to fit the model. Necessarily when considering climate change the system we are projecting will not function in the same way as the present climate that was used to construct the model in the first place. When considering such changes the output can be measured depending on the intention of the research. Niche analysis has been used to consider future local extinction and growth of conservation areas (Araujo & Williams, 2000; Wiens *et al*., 2011), the advancing spread of an invasive species (Broenniman *et al.*, 2007; Broenniman & Guisan, 2008), and general movements of species as a result of climate change (Gasner *et al*., 2010; Johnson *et al*., 2011; Lucey *et al*., 2010; Pounds *et al.*, 1999; Sagarin *et al*., 1999).

Human Ecological Niches

Humans expand their realised niche by technological means. Humans occupy nearly the entirety of global climate space (Fig. 2.1). This ingenuity and adaptability of human technology is one key reason for their success as a species, but both agricultural and industrial infrastructure are adapted within certain climates and changes in climate can drastically affect their function. For instance, the predicted shifts in monsoon periods in Indonesia threaten to destroy the traditional cycle of crop harvesting, which has been adapted for predictable timings and duration of the monsoon (Naylor *et al*., 2001). A change in temperature can translate to a shortening or lengthening in growing season, and indeed the productivity of agriculture in some regions of northern Canada and Scandinavia is set to increase as growing seasons lengthen due to shorter annual frost periods (McCarty, 2002; Tucker *et al*., 2001) and a lessening of extreme winter conditions (Fig. 2.4). A change in temperature can also mean greater heat-stress and lower agricultural output, a key concern in many semi-arid areas such as the Sahel (Rozenzweig *et al*., 2001), and temperature in many arid areas is set to increase (Fig. 3.4). The effect of a temperature increase is not isolated. A temperature increase within sub-Saharan Africa is linked to weather patterns, how precipitation gradients form and the growing cycle of the crops themselves. Since all are linked, the effect of temperature alone is meaningless but can be used as an indicator of other effects. For example, four climate factors: temperature, precipitation, and annual temperature and precipitation variability can reasonably predict the growing season for many agricultural crops (Samson *et al*., 2011; Stephenson, 1998), even though there are many more factors that can be measured. As a whole, human distribution is not linked purely to climate factors, when using a strict definition of physiological limits, but by expanding the definition to include technological advancement (thus making human distribution a measure of realised rather than fundamental niche) it is possible to apply a niche model to human populations.

Climate change in climate space

Given that humans have adaptation limits and links to biotic factors through agriculture, a few measures of climate change risk can be tentatively suggested. The first, and simplest relate to climate change velocity (Loarie *et al*., 2005). The faster the climate changes and becomes dissimilar to previous conditions, the more unpredictable and detrimental the effects are likely to be. This is the case in human and non-human systems. Whether humans will move to track familiar climate conditions, as is frequently assumed in animal ecology, is of some debate and is driven by many sociological factors (Black *et al.*, 2008). Since our constructed climate space describes multiple climate factors at once (Fig. 2.1), instead of trying to compare temperature and precipitation changes, we simply measure the movement of a gridcell in climate space between the present and 2050. Areas that will undergo the most change, and be most dissimilar from their current climates, are centred around South-East Asia, central Africa, regions of the Andes, the northern Amazon, Greenland and New Zealand (Fig. 3.1). Within these regions the magnitude of climate change will be widespread and extremely high.

Another primary metric of risk used in this report focuses on novel and extinct climate space. Our current understanding of climate is necessarily based on what we can measure and model as it exists now. While we have some proxy measurements and understanding of climate outside of today's range of climate factors using paleoecological systems (e.g. Braconnot *et al*., 2002; Fricke *et al*., 1998), our system models will always be more accurate within the parameters they were created, without the need for extrapolation. Novel climate exists outside the extant climate conditions and can indicate either the increase of a climate variable outside of today's boundaries, for example increased mean annual temperature to an extent that does not exist today, or a novel combination of climate factors. There appears to be clear links between an area that will experience high levels of climate change and its likelihood to develop novel climate

(Fig. 3.1; 3.2). It is in similar areas that the most novel climate will appear, especially in south-east Asia from Bangladesh to Papua New Guinea and the Amazon (Fig. 3.2). Those areas that will change rapidly but do not develop novel space often instead display areas of extinct space, especially Greenland, New Zealand and areas of Siberia (Fig. 3.3).

Development of such climate represents something outside of our understanding and as such presents a risk to any ecosystems or human populations that are present (Williams *et al*., 2007). The inverse, the extinction of climates, was also included for its potential for loss of biodiversity and climates that benefit human populations (Ohlemüller *et al*., 2006).

If one assumes the extremes of climate are less hospitable to human populations this gives another potential measure of risk, the more extreme climate becomes, either as a dry area become drier or cold area becomes colder, the more inhospitable it becomes. We dub this a measure of marginality, as the more a species nears the edges of a niche the greater the difficulty in surviving and breeding successfully. This assumes that the most normal areas of climate are, or will become, the most heavily populated, and that marginal areas are less so and that, as climate changes and moves towards the centre, the climate will become more clement, and as it moves away it will become less. We have noted already that this is not always the case in humans and humans inhabit the hot and wet edge of climate space at a high population density right up until the very edge of existing climate change (Fig. 3.1; 3.4). Whether changes in temperature or precipitation in these areas would have positive or negative effects is uncertain, but in areas that develop novel climate (Fig. 3.2) or experience especially high levels of climate change (Fig. 3.1) there is a great potential for risk to human populations.

By looking at those areas that experience very high levels of climate change (Fig. 3.1) and a high likelihood of emerging novel climate (Fig. 3.2), they are often related to the direction and marginality of the regions within climate space. Regions that match both of these criteria are located in marginal climate space, either on the cold dry extreme or hot extreme (Fig. 3.1; 3.2; 3.4). Climate space as a whole shows a shift towards higher average global temperatures (see IPCC, 2007b) and towards less rainfall in many already dry areas. As such, climate space as a whole demonstrates a general shift in one direction, rather than many (Fig. 3.4). Areas on one end, that of hot and wet regions on the edge of climate space, shift outside of climate space and develop novel climate (Fig. 3.2; 3.4). At the other extreme, climates that are rare and marginal in regions that are cold and dry move towards the centre and the climate that existed there becomes extinct (Fig. 3.3; 3.4). While many areas do not obey these general patterns, such as parts of the northern Amazon which becomes more centralised in climate space (Fig. 3.4), there is a certain trend in movement in climate space depending on an area's position within it. Areas that are marginal are also the areas that in general display the highest levels of climate change, and while areas in central climate space do change they mostly do not demonstrate the same magnitude of climate change as marginal climate space

Additive risks from climate change

The measures of climate change developed so far in this thesis are important for estimating the level of risk presented by climate change, but the responses of humans to climate change, like climate change itself, will not be uniform across the globe (IPCC, 2007a; McMichael *et al*., 2006; Walther *et al*., 2002). Areas of poverty, instability and existing humanitarian concerns will be more at risk from change than regions with stable and wealthy governmental infrastructure. There is a risk that climate change adds an additional facet of risk to already suffering areas. Previous studies of natural disasters and responses to them provide examples of how resilience to disaster can be very variable (Cutter *et al*., 2008). Wealth plays a major role and allows people to either support themselves or the government to intervene. The population density of an area also is a measure of the risk experienced overall. Resilience to change is also affected by the level of available national and international support, transport, health-care, aid and similar.

Several key hotspots were selected from the literature that are generally agreed to have major vulnerabilities to internal threats, such as war, disease, drought and poverty. From various sources the hotspots selected were the Andes (Malcolm *et al.*, 2002; Schubert *et al.*, 2006), Central Asia (Schubert *et al.*, 2006), South-East Asia (IPCC, 2007b; Warner *et al*., 2009), the Sahel (Ehrhart *et al.*, 2008; Schubert *et al.*, 2006; Warner *et al*., 2009; Werz & Conley, 2012; UNEP, 2011) and China (Schubert *et al*., 2006) (Fig. 4.1). These hotspots were selected and compared to our own indicators of climate change risk. The main three risk variables used are: the magnitude of climate change experienced, local GDP and population density and trends (expanding population centres etc.). An area is described as a hotspot due to a convergence of many factors that make it vulnerable, for example the Sahel has areas of extreme poverty that are badly affected by periods of drought, disease and political instability (Table 3.1). However, all these are difficult to measure, hence the inclusion of the indicator variables of local GDP and population trends.

In our study, hotspots possessed higher than normal population growth trends in the future, thus increasing pressure on local infrastructure and putting more people at risk (Fig. 4.3). Regional GDP was variable within selected hotspots, but all exhibited some areas of very low GDP, although this was not uniform (Fig. 4.2). Climate change was significantly higher in each hotspot investigated, especially in South-East Asia, unsurprisingly as these areas were highlighted already from analysis in Chapter 3 (Fig. 3.1; 3.2). However the Sahel, which is the focus of multiple international aid reports (Ehrhart *et al*., 2008; Schubert *et al*., 2006; Warner *et al*., 2009; Werz & Conley, 2012; UNEP, 2011), does not appear to be particularly prominent within this measure (Fig. 3.1; 3.2). It seems each of these hotspots will be severely affected by climate change, even though these are just those areas that are least able to cope with such a drastic change.

Using the three indicators of risk, high rates of climate change, low local GDP and high population growth, we modify the results of climate change distance across the world by including a standardised sociological risk element and derive our own hotspots as areas most at risk from climate change. The results have both similarities and dissimilarities to the hotspot analysis; the top 5% at risk regions using this metric include wide regions of South-East Asia (again this comes across as a key hotspot), South America, the Andes, Central Asia and India and northern China, but once again the Sahel does not appear prominently (Fig. 4.5; 4.6). This provides an example how translating complex qualitative reasons of risk into quantitive factors measurements is not a simple process, as it is in the nature of the political background, and the increasing occurrence of extreme events, such as extreme droughts, that are not included in this analysis, that determines the risk and vulnerability of an area. Nevertheless, this form of combined analysis allows a construction of risk across the world to be built. From combining multiple climate factors we can estimate change more comprehensively and the nature of change at a gridded level using the best climate models available for the future. The reoccurrence of several regions throughout, from climate change magnitude, marginality, novel/extinct space and in hotspot analysis, suggests key areas of risk from climate change in the future.

Reactions to climate change

Human responses to climate change are likely to be as diverse and variable as humans themselves are. How a person or population reacts depends on their location, their wealth, education, opportunities for movement, cultural background and the level of risk they face (Black *et al*., 2011; Grothmann & Patt, 2005). It is a mistake to assume that those populations at risk, even those with fewest resources and that are poverty-stricken, will demonstrate uniform responses. However, it is certain that drastic changes in weather, agricultural conditions and frequency of extreme weather events will have a great impact on population living standards, economics and migration patterns. For example, the continuing instability and increasing dryness and frequency of droughts has caused a large migration flow across the Sahel towards southern Europe, and this trend is expected to increase in future (Werz & Conley, 2012). A focus of many reports is the increasing instability and potential for conflict caused by increased numbers of refugees and migration due to climate change (Barnett & Adger, 2007; Nordås & Gleditsch, 2007; Reuveny, 2007; UNEP, 2011). The potential for disruption of food-sources, transportation, trade and humanitarian crises is also a cause for concern raised in many reports. To use the framework of bioclimate modelling, it is often assumed that a shift in niche in space will correspond with a movement of species to match the niche, with the potential for lag if dispersal of the species is slower than the change taking place (Chen *et al*., 2011). Assuming the same in humans has limitations, as migration is limited by international borders and the destruction of available environment for settlement reduces the capability of movement. As such, the destruction of livelihoods due to sea-level rises, collapse in agriculture, extreme weather events or any of the other consequences of climate change presents a huge risk to organisations around the world.

Instability, heightened death-toll and large population movements are the most likely outcomes from rapid climate change that is not countered by preparation and local mitigation measures. Analysis that helps highlight those areas that face the highest relative risk is one step to prioritise and focus further reports and to help form responses to counter these risks. The areas listed here that face rapid climate change, novel or extinct climate and possess regions of poverty, high population centres and other sociological factors that indicate a high vulnerability and low resilience to the change and instability they are likely to face. This is despite the fact that these countries are also some of the least responsible for the anthropogenic climate change that has been produced. In particular the rapid and unpredictable changes in climate in South-East Asia, Central Africa, the Andes, and the northern Amazon deserve scrutiny and response.

Conclusions

Taking three linked fields of methodology: climate change science, ecological niche modelling, and human sociological factors, we attempt to produce a combined method of analysing climate change and risk in the next 50 years. Humans inhabit nearly all of Earth's available climate space, but they are not distributed evenly. By correlating climate space and human population density we firstly suggested climatic reasons for human distribution. Humans are more scarcely present in cold, extreme regions of climate space as well as dry, hot climate space, more common in central temperature climate space including some heavily populated areas, and are present in both very low and very high population densities in extreme climate space with high precipitation and temperature values. Marginal climate space is not only more extreme, but is more prone to high levels of climate change and developing novel or extinct climates. Populations within these areas of high climate change risk are of particular concern. To analyse which of these areas of climate change risk will be most vulnerable, we introduced sociological measures to find those regions with the highest levels of climate change and population density and lowest regional GDP or resources to overcome the challenges of climate change. Many of the areas already mentioned in the previous forms of analysis appeared again as high risk, so can be suggested as those areas that will experience the highest risk from climate change and will also be the least equipped to deal with it. Areas particularly highlighted are central and South-East Asia, including Indonesia, Papua New Guinea, the Philippines, Bangladesh, India and Vietnam, central Africa, and areas of the Amazon and the Andes. It now seems unlikely that even drastic reductions in carbon emissions will stop all changes and increases in risk across the world in the next century, therefore for these vulnerable regions the focus must also be on preparation and mitigation by increasing resilience and evasion of the worst of the effects of changing climate to avoid an unprecedented humanitarian crisis in multiple areas of the world.

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